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SPI Report

SUMMARY OF SOLAR CELL DATA FROM THE LONG DURATION EXPOSURE FACILITY (LDEF).

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The contractor has obtained and reviewed data relating solar cell assemblies (SCAs) flown as part of the following LDEF experiments: the Advanced Photovoltaic Experiment (S0014), the Solar Array Materials Passive LDEF Experiment (A0171), the Advanced Solar Cell & Coverglass Analysis Experiment (M0003-4), the LDEF Heat Pipe Experiment (S1001), the Evaluation of Thermal Control Coatings & Solar Cells Experiment (S1002), and the Space Plasma-High Voltage Drainage Experiment (A0054). Where possible, electrical data have been tabulated and correlated with various environmental effects, including meteoroid & debris impacts, radiation exposure, atomic oxygen exposure, contamination, UV radiation exposure, and thermal cycling. The type, configuration, and location of all SCAs are documented here. By gathering all data and results together, a comparison of the survivability of the various types and configurations can be made.

Generally, silicon and gallium arsenide cells were flown of various sizes ranging from 2cm X 2cm to 5.9cm X 5.9cm. Most SCAs were conventionally configured with a glass cover bonded to the cell with a silicone RTV adhesive. Both conventional top-bottom contact and wrap-around contact configurations were flown. SCAs with wrap-around contacts appear to be more survivable than SCAs with conventional top-bottom contacts, with *FF* degrading less for the former configuration. For silicon cells, higher base resistivity produces better radiation hardness with reduced degradation occuring. A base resistivity of 10Ω.cm gives 3% reduction in I_{SC} and 18% reduction in P_{MAX}, whereas 1Ω.cm gives 9% reduction for I_{SC} and 23% for P_{MAX}. Also, radiation hardness is a function of cell junction depth, with shallower-buried junctions being more susceptible to radiation damage than deeper-buried junctions.

Gallium arsenide cells were extremely survivable with almost no degradation in *FF*. However, I_{SC} was down by 10% in the specific SCA configuration presented here, indicating cover and/or contamination effects. It is also possible that space exposure reduced the cell photocurrent generation efficiency which would have also produced a reduction in I_{SC} not necessarily accompanied by degradation in the cell current-voltage profile.

For conventional SCAs with ceria-doped microsheet covers and various silicone RTV adhesives (~35μm thick) experienced no more than a 3% reduction in I_{SC}, attributable to UV-darkening. For fused silica covers and a thin layer (~30μm) of DC93-500 adhesive, UV-induced darkening was also of negligible importance, resulting in I_{SC} losses of between 2% and 3%. There was also some indication that I_{SC} reductions correlate with cover thickness, confirming the hypothesis that that UV-darkening is the cause of such reductions. UV rejection filters appeared to produce no discernible or beneficial effects within this data set.

M&D damage varies from micrometer-scale craters in cell covers to millimeter-scale complete penetration of the SCA stack through to the underlying substrate or faceplate. Losses in I_{SC} are proportional to the damage area, this being a minimal effect. Where cover pentration occurs significant degradation in cell electrical performance can occur from increases in R_S due to cell cracking and/or decreases in R_{SH} due to p-n junction shunting. Resultant degradation of FF and P_{MAX} can occur. It must be emphasized that penetrations of the cell are not always degrading. The possibility of cell resistance changes are related to the amount of metallic residue left in the crater and/or the degree and extent of cell structural cracking. Uncovered cells are prone to M&D impact-induced shunting of the cell junction.

BE-225HUP co-polymer conformal covers suffered extreme erosion. GE X-76 polyimide conformal covers were extensively eroded, although to a lesser extent than the BE-225HUP covers. Hard-coat silicone covers suffered some erosional losses and top surface "crazing," while soft-coat silicone covers suffered minimal loss. Where covers were lost the cells underwent significant damage due to radiation exposure. FEP Teflon® covers provided negligible protection against M&D impact damage, although they did provide sgnificantly better radiation protection than polymer covers. UV darkening was a problem for FEP Teflon® covers, generating 10% to 40% reductions in I_{SC}. In general, polymer covers provide less protection than conventional glass covers, the cell FF being most affected, indicating worse radiation protection. DC93-500 silicone RTV used as a conformal cell cover is not a good option as UV darkening becomes significant for the thicknesses required to provide some level of radiation protection. FEP Spraylon covered cells exhibited significant degradation in V_{OC} and FF indicative of cell shunt resistance decrease and/or carrier recombination increase.

Contamination modifies the transmissive/reflective properties of the cover front surface. Such surface contamination was found to be "scrubbed" by AO exposure since the contamination levels on the leading edge were almost negligible in comparison with trailing edge levels. Trailing edge contamination was measured to be ~100Å thick, mainly comprising silicon (Si), carbon (C), and oxygen (O). About half of the samples exposed showed trace levels of nitrogen (N), fluorine (F), and tin (Sn), with some silicone-based contamination also present. With regard to ITO conductive coatings, there is no apparent contamination-induced effects. Also, thermal emissivity and solar absorptivity for SCAs are affected marginally by contamination.

SCA cover AR coatings such as magnesium fluoride (MgF_2) and thorium fluoride (ThF_4) underwent significant changes due to AO exposure. Leading edge MgF_2 coatings were contaminated by fluorinated organic compounds and suffered significant oxygen replacement of flourine atoms. Fluorine was completely removed from ThF_4 leading edge coatings, although no oxides were detected. Uncoated SiO_2 was inert and suffered no molecular changes.

Severe AO erosion of exposed silver interconnects occurred, resulting in open circuits on some badly affected SCAs. Kapton-H® insulation suffered severe AO erosion where fully exposed. Some unprotected wrap-around contacts suffered severe AO erosion, resulting in a significant increase in SCA series resistance. ITO conductive coatings were significantly degraded by AO, resulting in twofold increase in coating resistance. A further degradation mode for conductive coatings was observed caused by M&D impacts where cover cracking leads to electrical isolation of parts of the cover. Electrical bond pads (EBPs) used to make connections to cover conductive coatings were found to be susceptible to the space environment. Adhesive-based EBPs suffered decreases in resistivity, probably due to material outgassing, whereas solder-baseds EBPs suffered increases in resistivity, most likely due to the thermal expansion mismatch at the EBP-cover interface.

SCOPE OF WORK

The Scope of Work is presented here for completeness as taken from the NASA Delivery Order Proposal and Acceptance package for this project (delivery order no. 17, contract NAS8-39131).

> The Long Duration Exposure Facility (LDEF) was composed of many separate experiments, some of which contained solar cells. These solar cells were distributed at various positions on the LDEF and, therefore, were exposed to the space environment with an orientational dependence.
>
> Task 1: The contractor shall gather and summarize the LDEF solar cell data. This shall include, but not be limited to, the following data as available.
>
> > **solar cell description**
> > substrate composition and thickness, crystal orientation, anti-reflective coating composition and thickness
> >
> > **pre-flight characteristics**
> > V (open circuit), I (short circuit), V (at maximum power), I (at maximum power), maximum power and efficiency
> >
> > **post-flight characteristics**
> > V (open circuit), I (short circuit), V (at maximum power), I (at maximum power), maximum power and efficiency
>
> The position, location and orientation of each solar cell on the LDEF shall be defined, as available, by the contractor.
>
> Task 2: perform solar cell measurements as necessary to complete task 1.
>
> Task 3: provide an analysis summary and conclusion of findings related to Space Environmental Effects (SEE) on solar cells in Low Earth Orbit (LEO).

This report will address the space environmental effects on solar cells and solar cell assemblies (SCAs), including electrical interconnects and associated insulation blankets where flown in conjunction with solar cells. Environmental effects on cell covers shall be considered when the cover was flown as part of a SCA.

GLOSSARY OF TERMS & ACRONYMS

AO .... atomic oxygen
APEX.............. Advanced Photovoltaic Experiment
AR.................... anti-reflection
ASEC.............. Applied Solar Energy Corporation
BE.................... Bergstrom & Associates
BSF .... back surface field
BSR .... back surface reflector
CTM .... contamination
CVD................ chemical vapor deposition
FEP .... fluro-ethylene-polymer
FF .... fill factor = $P_{MAX}/(I_{SC} V_{OC})$
FLT .... flight
FS .... fused silica
GE .... General Electric Company of America
GEO .... geo-stationary earth orbit
GSFC.............. Goddard Space Flight Center
HRL................ Hughes Research Laboratories
I-V .... current-voltage
IDP.................. interplanetary dust particle
I_{MP} .... current at maximum power
I_{SC} .... short circuit current
ITO .... indium tin oxide
JPL.................. Jet Propulsion Laboratory
LEO .... low Earth orbit
LeRC .... Lewis Research Center
LMSC .... Lockheed Missiles & Space Company
M&D............... meteoroid and debris
MBB .... Messerschmitt-Bolkow-Blöhm
MD.................. meteoroids and debris
MOS .... metal-oxide-semiconductor
MSFC .... Marshall Space Flight Center
n/d .... not defined
OCLI .... Optical Coating Laboratory Incorporated
OTS .... Orbital Test Satellite (European Space Agency)
pct.................... percentage point(s)
%...................... per cent
P_{MAX} .... maximum power = $I_{MP} \cdot V_{MP}$
RAD................ radiation
R_S..................... series resistance
R_{SH}.................. shunt resistance
RTV .... room temperature vulcanized
SAMPLE .... Solar Array Materials Passive LDEF Experiment
SCA .... solar cell assembly
SDP .... space debris particle
SMM............... Solar Maximum Mission
TBD .... to be determined
UV .... ultra-violet
VHBS .... very high blue sensitivity
V_{MP} .... voltage at maximum power
V_{OC} .... open circuit voltage

INTRODUCTION

The space environment in earth orbit has been extensively studied and documented. The most serious factors influencing solar array systems and components are the local radiation environment, thermal cycling effects, local plama density, neutral particle density, spacecraft surfaces outgassing/effluent products, and the meteoroid and debris flux. The radiation environment (proton, electron, and photon) is complex and depends upon such factors as orbital altitude, inclination, and current solar activity levels. The effects of these particles and electromagnetic radiation can cause major changes in the properties of insulators and semiconductors by ionization, atomic displacements or local changes due to chemical reactions. Atomic oxygen exposure is known (ref. 1) to be especially damaging for materials which suffer oxidation easily. Solar cell silver interconnects have been found to be particularly susceptible as have numerous polymeric materials such as Kapton®.

Where spacecraft surfaces are exposed to the space particulate (meteoroid and debris -M&D) environment the threat of hypervelocity micro-particle cratering, perforation, and impact-induced electrical breakdown (both volume breakdown and surface flashover) exists. The term *"hypervelocity micro-particle impact"* implies impact by micron-scale to sub-millimeter-scale space particles, including space debris particles (SDPs) and interplanetary dust (meteoroids) particles (IDPs) at velocities in excess of 4-6 km/s. Such particles typically impact spacecraft in LEO at average velocities in the range 7-25 km/s and, because of their excessive kinetic energy, generate shock waves in target materials, liberate copious amounts of ejecta and initiate the production of hot plasma.

Space Environment-induced Solar Cell Degradation Phenomena

For solar cell assemblies (SCAs) the space environment can be especially abrasive. Essentially, SCAs are affected by:

- Proton radiation: causing displacement damage in the solar cell.
- M&D impact damage: penetration of SCA covers, cratering in cover, cratering in cell, total penetration of SCA to substrate.
- Atomic oxygen: oxidation and erosion of susceptible materials (e.g. silver inter-connects, Kapton & other polymer insulators).
- UV radiation: darkening of covers and adhesives, reducing the light intensity at the cell and thus the output power.
- Thermal cycling: possible delamination of structures where significant thermal mismatches exist between different materials.

- Contamination: changes in cover front surface optical characteristics leading to light scattering and changes in transmission and reflection coefficients.

To allow for discussion of the various cell performance degradation phenomena it is instructive to consider the solar cell equivalent circuit (figure 1), comprising a current source in parallel with a diode, combined with a parallel shunt resistance (R_{SH}) and a series resistance (R_S). Figure 2 shows a typical SCA cross-section to facilitate discussion of environmental effects on SCAs. Also included are typical current-voltage profiles indicating various effects such as increasing R_S (figure 3), decreasing R_{SH} (figure 4), increasing minority carrier diffusion current (figure 5), and increasing depletion region recombination current (figure 6).

The sum total of space environmental effects on spacecraft materials, components, and systems, can only be evaluated by long term exposure. Therefore, NASA designed, flew, and retrieved the LDEF spacecraft, which remained in orbit for 69 months from April 1984 to January 1990. Included in the experiment inventory were several experiments designed to measure the effects of long duration exposure to the space environment on solar array materials, solar cells, and associated array manufacturing technologies. The purpose of the work reported here was to collect, collate, and summarize data and results pertaining to SCAs flown on LDEF.

LDEF ORIENTATION & EXPERIMENT EXPOSURE GEOMETRY

The LDEF was deployed into Earth orbit on 7 April 1984 at a time of near-minimum solar activity and was retrieved 69 months later on 12 January 1990 at a time of near-maximum solar activity (ref. 2) after completing 32,422 orbits. The spacecraft flew in a circular orbit, inclined at 28.5°, with an initial altitude of 257 nm (476 km). On retrieval, the orbit had decayed to an altitude of approximately 179 nm (332 km).

A passive, gravity-gradient 3-axis stabilization scheme was utilized for attitude control. Figure 7 shows the spacecraft structural configuration and identification of experiment locations relative to the spacecraft body coordinate system. The 12 faces (experiment rows) of the structure are numbered 1 through 12 in a clockwise direction when looking at the Earth-facing end. The 6 longitudinal locations on each row are identified as Bay A through Bay F starting at the Earth end of the spacecraft. Nominally, the LDEF was to fly orientated with the Row 9 surface normal (+Z axis) parallel to the spacecraft velocity vector and the spacecraft +X axis (Space-facing end normal vector) parallel to the orbit radius vector. In reality, the spacecraft was yawed 8.1° to starboard and pitched 2° forward. Figure 8 shows the spacecraft attitude relative to the Earth and the effect of the 8.1° yaw on the relative orientations of the various experiment tray rows.

DEFINITION OF EXPERIMENTS INCLUDING SOLAR CELL ASSEMBLIES

Six LDEF experiments contained solar cell assemblies or components. These are listed in Table 1. Most cells were configured individually so that pre-flight and post-flight current-voltage characteristics could be determined on a cell by cell basis. A few cells comprised active power sources for experiments (e.g. A0054 and S0001)and therefore operated under load throughout their exposure duration. Finally, some cells were exposed passively, without any electrical connections for current-voltage (I-V) characterization (e.g. A0171 GSFC test plate), to allow post-flight structural analyses to be performed.

PI	Cell Type	Number	Experiment/Description	Location SFCE normal vector
NASA LeRC Brinker, D.J.	Si, GaAs	155	S0014 Advanced Photovoltaic Experiment (APEX)	E09 8.1° off-RAM
NASA MSFC Whitaker, A. F.& Young, L.E.	Si	4 modules & 5 cells	A0171 Solar Array Materials Passive LDEF Experiment (SAMPLE)	A08 8.1° off-RAM
NASA LeRC Brinker, D.J.	Si	20	A0171 Solar Array Materials Passive LDEF Experiment (SAMPLE)	A08 8.1° off-RAM
JPL Stella, P.M.	Si	30	A0171 Solar Array Materials Passive LDEF Experiment (SAMPLE)	A08 8.1° off-RAM
NASA GSFC Gaddy, E.	Si	43	A0171 Solar Array Materials Passive LDEF Experiment (SAMPLE)	A08 8.1° off-RAM
USAF Wright-Patterson AFB Trumble, T.M.	Si, GaAs	70	M0003-4 Advanced Solar Cell and Coverglass Analysis	D09 & D03 8.1° & 171.9° off-RAM
NASA GSFC Tiller, S.	Si	4 arrays	S1001 LDEF Heat Pipe Power Sub-system	H01 space end
MBB Preuss, L.	Si	3	S1002 Evaluation of Thermal Control Coatings and Solar Cells	E03 171.9° off-RAM
TRW Yaung, J.Y.	Si	12	A0054 Space Plasma High Voltage Experiment	B04 & D10 158.1° & 21.9° off-RAM

Table 1. *Summary of all LDEF experiments containing solar cell modules and/or components (ref. 3).*

LDEF Location: **E09**

Experiment Identification: **S0014**

Experiment Title: **Advanced Photovoltaic Experiment**

The Advanced Photovoltaic Experiment (APEX) was originally designed to provide reference solar cells for laboratory experiments and testing as well as to investigate the solar spectrum and the effects of long term exposure of solar cells to the low Earth orbit (LEO) environment (ref. 4). The experiment was located in Bay E09, offset from the spacecraft flight vector by 8.1°. It was exposed to the following space environments:

Sun Hours:	11155.87	ESH	(day = 2106)
Full Spectrum Solar Fluence:	5.49e+6	$J.cm^{-2}$	
UV Radiation (0.2-0.4µm):	4.38e+5	$J.cm^{-2}$	
AO Fluence:	8.72e+21	$atoms.cm^{-2}$	
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$	
Electron Fluence (0.05-3.0MeV):	TBD	$electrons.cm^{-2}$	
Meteoroid & Debris (F-0.5mm):	7.9±0.6	$m^{-2}.yr^{-1}$	

There were TWO (2) sub-elements for the APEX, one provided by NASA LeRC and the other provided by NASA MSFC. The NASA LeRC element was designed to accommodate 155 cells, 144 of which were silicon (Si) cells with 11 being gallium arsenide (GaAs). The NASA MSFC element comprised at least 10 cells, two with concentrator elements. Cell sizes ranged from 2cm X 2cm to 5.9cm X 5.9cm. Various solar cell assembly configurations with different cover materials, anti-reflection coatings, and UV filters were flown. Currently, post-flight data exist for the following cells and modules (refs 4-6);

<u>NASA LeRC Silicon Cells</u>

ISC#93	5.9cm X 5.9 cm; wrap-around contacts; FS cover
ISC#95	5.9cm X 5.9 cm; wrap-around contacts; FS cover
ISC#100	5.9cm X 5.9 cm; wrap-around contacts; FS cover
ISC#64	2cm X 2cm; conventional contacts; n/d cover
IV#7	2cm X 2cm; conventional contacts; 7940 FS cover
ISC#112	2cm X 2cm; VHBS; conventional contacts; 7070 V-groove cover
ISC#114	2cm X 2cm; textured surface; conventional contacts; FS cover
ISC#63	2cm X 2cm; BSR/BSF; 1Ω.cm; no cover
ISC#83	2cm X 2cm; BSR/BSF; 10Ω.cm; no cover

NASA LeRC Gallium Arsenide Cells

ISC#111	1.3cm X 1.6cm; MOS heterostructure; n/d cover
ISC#71	2cm X 2cm; 0.50μm junction depth; FS cover
ISC#76	2cm X 2cm; 0.50μm junction depth; no cover
ISC#77	2cm X 2cm; 0.35μm junction depth; no cover

NASA MSFC Silicon Cells

B32	2cm X 4cm; wrap-around contacts; DC 93-500 adhesive cover
B33	2cm X 4cm; wrap-around contacts; DC 93-500 adhesive cover
B34	2cm X 4cm; wrap-around contacts; LMSC FEP Spraylon cover
B35	2cm X 4cm; wrap-around contacts; LMSC FEP Spraylon cover
B36	2cm X 4cm; wrap-around contacts; ceria-stabilized microsheet cover
B37	2cm X 4cm; wrap-around contacts; ceria-stabilized microsheet cover
B38	2cm X 4cm; wrap-around contacts; FS cover
B41	2cm X 4cm; wrap-around contacts; FS cover
B57	2cm X 4cm; wrap-around contacts; n/d cover
CONC-1	2cm X 4cm; wrap-around contacts; FS cover
CONC-2	2cm X 4cm; wrap-around contacts; FS cover

NASA LeRC Silicon Cells Data

ISC#93 M-3	ASEC 5.9cm X 5.9cm Silicon n-on-p cell; wrap-around contact on each corner.				
M&D damage:	Small crater in coversheet; no penetration of coversheet.				
pre-FLT:	I_{SC} = 1.38A	V_{OC} = 0.569V	I_{MP} = 1.23A	V_{MP} = 0.445V	FF = 69.6
post-FLT:	I_{SC} = 1.37A	V_{OC} = 0.570V	I_{MP} = 1.20A	V_{MP} = 0.446V	FF = 68.3
Δ_parameter:	-0.7%	+0.2%	-2.4%	+0.2%	-1.3pct
ΔP_{MAX}:	-2.2%				

ISC#95 M-5	ASEC 5.9cm X 5.9cm Silicon n-on-p cell; wrap-around contact on each corner; coversheet 152μm (6 mil) thick fused silica (SiO_2).				
M&D damage:	Not significant.				
pre-FLT:	I_{SC} = 1.20A	V_{OC} = 0.584V	I_{MP} = n/d	V_{MP} = n/d	FF = 70.1
post-FLT:	I_{SC} = 1.20A	V_{OC} = 0.594V	I_{MP} = 1.07A	V_{MP} = 0.442V	FF = 66.8
Δ_parameter:	-0.3%	+1.7%	n/d	n/d	-3.3pct
ΔP_{MAX}:	-4.4%				
	3.3pct loss in FF can be attributed radiation damage; -> increase in series resistance.				

ISC#100 M-9	ASEC 5.9cm X 5.9cm Silicon n-on-p cell; wrap-around contact on each corner.				
M&D damage:	Large crater in coversheet; penetration of coversheet to solar cell; solar cell cracked across 90% of width; coversheet cracked across whole width.				
pre-FLT:	I_{SC} = 1.22A	V_{OC} = 0.577V	I_{MP} = 1.86A	V_{MP} = 0.471V	FF = 73.4
post-FLT:	I_{SC} = 1.22A	V_{OC} = 0.580V	I_{MP} = 1.05A	V_{MP} = 0.396V	FF = 58.8
Δ_parameter:	-0.3%	+0.5%	-43.5%	-15.9%	-14.6pct
ΔP_{MAX}:	-52.5%				
	14.6pct loss in FF is attributed to the crack in the solar cell; -> increase in series resistance.				

ISC#64 NA-9	2cm X 2cm Silicon n-on-p cell.				
M&D damage:	Large crater in coversheet (1.8mm dia.); penetration of coversheet and cell to aluminum faceplate; no coversheet or cell cracking.				
pre-FLT:	I_{SC} = 0.136A	V_{OC} = 0.599V	I_{MP} = 0.124A	V_{MP} = 0.497V	FF = 75.1
post-FLT:	I_{SC} = 0.129A	V_{OC} = 0.503V	I_{MP} = 0.116A	V_{MP} = 0.398V	FF = 70.1
Δ_parameter:	-5.1%	-16.0%	-6.5%	-19.9%	-5.0pct
ΔP_{MAX}:	-25.1%				
	96mV drop in V_{OC} due to decrease in shunt resistance across cell p-n junction at impact site; 5.1% drop in I_{SC} attributed to area loss (due to crater) and contamination.				

IV#7 B-1L	Spectrolab 2cm X 2cm Silicon n-on-p cell; Solar Maximum Mission satellite; base resistivity 10 Ω.cm; AR coating Ta_2O_5; coversheet 305μm (12 mil) thick Corning 7940 fused silica.				
M&D damage:	Not significant.				
pre-FLT:	I_{SC} = 0.163A	V_{OC} = 0.587V	I_{MP} = n/d	V_{MP} = n/d	FF = 73.3
post-FLT:	I_{SC} = 0.161A	V_{OC} = 0.580V	I_{MP} = 0.144A	V_{MP} = 0.473V	FF = 73.1
Δ_parameter:	-1.2%	-1.2%	n/d	n/d	-0.2pct
ΔP_{MAX}:	-2.9%				

ISC#112 B-2R	COMSAT Very High Blue Sensitivity 2cm X 2cm Silicon cell; typical GEO satellite; base resistivity 1 Ω.cm; AR coating Ta_2O_5; coversheet 762μm (30 mil) thick Corning 7070 glass V-grooved above n-contact fingers.				
M&D damage:	Not significant.				
pre-FLT:	I_{SC} = 0.160A	V_{OC} = 0.608V	I_{MP} = n/d	V_{MP} = n/d	FF = 78.0
post-FLT:	I_{SC} = 0.164A	V_{OC} = 0.609V	I_{MP} = 0.154A	V_{MP} = 0.508V	FF = 78.6
Δ_parameter:	+2.5%	+0.2%	n/d	n/d	+0.6pct
ΔP_{MAX}:	+3.1%				

ISC#114 B-4R	COMSAT Non-reflecting Textured Surface 2cm X 2cm Silicon cell; typical GEO satellite; base resistivity 10 Ω.cm; AR coating Ta_2O_5; coversheet 305μm (12 mil) thick fused silica (SiO_2).				
M&D damage:	Not significant.				
pre-FLT:	I_{SC} = 0.193A	V_{OC} = 0.578V	I_{MP} = n/d	V_{MP} = n/d	FF = 73.9
post-FLT:	I_{SC} = 0.189A	V_{OC} = 0.577V	I_{MP} = 0.176A	V_{MP} = 0.455V	FF = 73.2
Δ_parameter:	-2.1%	-0.2%	n/d	n/d	-0.7pct
ΔP_{MAX}:	-2.9%				

ISC#63 NA-10	Solarex 2cm X 2cm Silicon cell with back surface field and reflector; base resistivity 1 Ω.cm; AR coating n/d; NO coversheet				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.147A	V_{OC} = 0.595V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.2
post-FLT:	I_{SC} = 0.134A	V_{OC} = 0.530V	I_{MP} = 0.119A	V_{MP} = 0.424V	FF = 71.1
Δ_parameter:	-8.8%	-10.9%	n/d	n/d	-4.1pct
ΔP_{MAX}:	-23.3%				

ISC#83 B-21R	NASA LeRC 2cm X 2cm Silicon cell; base resistivity 10 Ω.cm; AR coating n/d; NO cover.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.150A	V_{OC} = 0.578V	I_{MP} = n/d	V_{MP} = n/d	FF = 74.5
post-FLT:	I_{SC} = 0.145A	V_{OC} = 0.533V	I_{MP} = 0.134A	V_{MP} = 0.394V	FF = 68.3
Δ_parameter:	-3.3%	-7.8%	n/d	n/d	-6.2pct
ΔP_{MAX}:	-18.3%				

NASA MSFC Silicon Cells Data

B32	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; DC93-500 cover.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = n/d P_{MAX} = 94.5mW	V_{OC} = n/d	I_{MP} = n/d	V_{MP} = n/d	FF = n/d
post-FLT:	I_{SC} = n/d P_{MAX} = 91.2mW	V_{OC} = n/d	I_{MP} = n/d	V_{MP} = n/d	FF = n/d
ΔP_{MAX}:	-3.5%				

B33	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; DC93-500 cover.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 118.4mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 109.2mW
ΔP_{MAX}:	-7.8%

B34	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; FEP Teflon (LMSC Spraylon) cover.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 113.5mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 103.3mW
ΔP_{MAX}:	-9.0%

B35	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; FEP Teflon (LMSC Spraylon) cover.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 109.4mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 88.8mW
ΔP_{MAX}:	-18.8%

B36	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; Pilkington 5.5mil ceria-stabilized microsheet cover with AR coating.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 118.0mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 116.1mW
ΔP_{MAX}:	-1.6%

B37	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; Pilkington 5.5mil ceria-stabilized microsheet cover with AR coating.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 114.0mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 115.0mW
ΔP_{MAX}:	+0.9%

B38	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; OCLI 6mil fused silica (SiO_2) cover with AR coating and UV filter.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 114.1mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 116.1mW
ΔP_{MAX}:	+1.8%

B41	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; OCLI 6mil fused silica (SiO_2) cover with AR coating and UV filter.
M&D damage:	n/d
pre-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 118.4mW
post-FLT:	I_{SC} = n/d V_{OC} = n/d I_{MP} = n/d V_{MP} = n/d FF = n/d P_{MAX} = 118.3mW
ΔP_{MAX}:	-0.8%

B57	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; cover n/d.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = n/d	V_{OC} = n/d	I_{MP} = n/d	V_{MP} = n/d	FF = n/d
	P_{MAX} = 109.6mW				
post-FLT:	I_{SC} = n/d	V_{OC} = n/d	I_{MP} = n/d	V_{MP} = n/d	FF = n/d
	P_{MAX} = 111.1mW				
ΔP_{MAX}:	+1.4%				

CONC-1	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; chemically etched surface; OCLI 6mil fused silica (SiO_2) cover with AR coating and UV filter.				
M&D damage:	n/d				
pre-FLT:	I_{SC} =	V_{OC} =	I_{MP} =	V_{MP} =	FF =
post-FLT:	I_{SC} =	V_{OC} =	I_{MP} =	V_{MP} =	FF =
Δ_parameter:	n/d	n/d	n/d	n/d	n/d
ΔP_{MAX}:	n/d				

CONC-2	ASEC 2cm X 4cm Silicon n-on-p cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for end wrap-around contacts; metalization Cr:Pd:Ag; contact thickness 4-8μm; Ta_2O_5 AR coating; schemically etched surface; OCLI 6mil fused silica (SiO_2) cover with AR coating and UV filter.				
M&D damage:	n/d				
pre-FLT:	I_{SC} =	V_{OC} =	I_{MP} =	V_{MP} =	FF =
post-FLT:	I_{SC} =	V_{OC} =	I_{MP} =	V_{MP} =	FF =
Δ_parameter:	n/d	n/d	n/d	n/d	n/d
ΔP_{MAX}:	n/d				

Gallium Arsenide Cells Data

ISC#111 A-2	JPL 1.3cm X 1.6cm metal-oxide-semiconductor (MOS) Gallium Arsenide heterostructure cell; coversheet n/d.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.018A	V_{OC} = 0.747V	I_{MP} = n/d	V_{MP} = n/d	FF = 78.6
post-FLT:	I_{SC} = 0.022A	V_{OC} = 0.746V	I_{MP} = 0.020A	V_{MP} = 0.606V	FF = 75.0
Δ_parameter:	+22.2%	-0.1%	n/d	n/d	-3.6pct
ΔP_{MAX}:	+14.7%				

ISC#71 NB-15L	HRL 2cm X 2cm Gallium Arsenide cell; base resistivity n/d; AR coating n/d; junction depth (D_j) = 0.50µm; coversheet 305µm (12 mil) fused silica (SiO_2).				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.123A	V_{OC} = 1.00V	I_{MP} = n/d	V_{MP} = n/d	FF = 79.0
post-FLT:	I_{SC} = 0.108A	V_{OC} = 1.01V	I_{MP} = 0.102A	V_{MP} = 0.863V	FF = 80.1
Δ_parameter:	-12.2%	+1.0%	n/d	n/d	+1.1pct
ΔP_{MAX}:	-9.4%				

ISC#76 NB-29R	HRL 2cm X 2cm Gallium Arsenide cell; base resistivity n/d; AR coating n/d; junction depth (D_j) = 0.50µm; NO coversheet .				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.117A	V_{OC} = 0.995V	I_{MP} = n/d	V_{MP} = n/d	FF = 78.5
post-FLT:	I_{SC} = 0.095A	V_{OC} = 0.930V	I_{MP} = 0.087A	V_{MP} = 0.761V	FF = 75.0
Δ_parameter:	-18.8%	-6.5%	n/d	n/d	-3.5pct
ΔP_{MAX}:	-27.6%				

ISC#77 NB-29L	HRL 2cm X 2cm Gallium Arsenide cell; base resistivity n/d; AR coating n/d; junction depth (D_j) = 0.35µm; NO coversheet .				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.117A	V_{OC} = 0.983V	I_{MP} = n/d	V_{MP} = n/d	FF = 77.5
post-FLT:	I_{SC} = 0.094A	V_{OC} = 0.898V	I_{MP} = 0.085A	V_{MP} = 0.748V	FF = 75.2
Δ_parameter:	-19.7%	-8.6%	n/d	n/d	-2.3pct
ΔP_{MAX}:	-28.7%				

Summary of ASEC 5.9cm X 5.9cm Silicon Cells

- SEVEN (7) cells, with wrap-around contacts at the corners, were flown, along with FOUR (4) similar cells with conventional top-bottom contacts. Little change in I_{SC} or V_{OC} was apparent for the wrap-around cells although there was an average drop of 2.0pct in *FF*. The conventional contact cells also showed little change in I_{SC} or V_{OC}, but the drop in *FF* ranged from 6-18pct.

Summary of COMSAT Very High Blue Sensitivity 2cm X 2cm Silicon Cells

- TWO (2) cells (ISC#112 and IV#9) of this configuration were flown. No apparent degradation in performance was noted within the bounds of experimental error. The 30 mil coversheet appears to provide complete charged particle radiation protection. Minimal UV-induced darkening of the coversheet and adhesive occurred.

Summary of COMSAT Non-reflecting Textured Surface 2cm X 2cm Silicon Cells

- TWO (2) cells (ISC#114 and IV#11) of this configuration were flown, employing a texturized surface to optimize photon absorption thus increasing I_{SC}.

- There was no significant M&D damage.

- The 12 mil thick coversheet provided adequate radiation protection and experienced minimal UV darkening resulting in negligible changes in I_{SC}, V_{OC}, and FF.

Summary of Uncovered LeRC Silicon Cells

- A comparison of cells ISC#63 and ISC#83 shows that a higher base resistivity reduces the degree of degradation in I_{SC} and V_{OC} parameters. However, the FF for the 10Ω.cm cell was degraded more than that of the 1Ω.cm cell. Reduction in FF is usually attributed to an increase in cell series resistance (see figure 3), which can be due to radiation damage and/or corrosion of contacts, but also may be due to an increase in carrier recombination in the depletion region (see figure 6).

- Uncovered cells are particularly prone to M&D impact-induced shunting of the cell junction since it is only 1-3μm below the cell upper surface. Sub-micrometer diameter M&D particles are able to penetrate the cell junction at the typical impact velocities experienced by LDEF (21.5km/s for IDPs and 9.8km/s for SDPs).

Summary of NASA MSFC Silicon Cells

- SCAs with polymer covers (cells B32 through B35) suffered greater degradation of P_{MAX} than SCAs with conventional glass covers.

- Cells B32 and B33, with Dow Corning DC93-500 silicone adhesive as a protective conformal cover, underwent degradation (magnitude n/d) in I_{SC}. Adhesive darkening is the most probable major contributor.

- Cells B34 and B35, with LMSC FEP Spraylon conformal covers, suffered degradation (magnitude u/d) in V_{OC} and FF, indicative of decreased cell shunt resistance. The cause of degradation is undefined at present.

- There is NO coherent data published for CONC-1 and CONC-2 cells.

Summary of Gallium Arsenide Cells

- Anomalous behavior existed for cell ISC#111, the MOS heterostructure cell. It experienced a 22.2% increase in I_{SC} which is unexplained by the principal investigators at present. They state that it is possible that the contamination film covering the coversheet surface may have served to improve the anti-reflection properties of the front surface of the coversheet.

- For the other conventional cells, ISC#71, ISC#76, andISC#77, the effect of the fused silica coversheet is to prevent the 18% - 19% drop in I_{SC} experienced by the uncovered cells. The uncovered cells also experienced a significant, 6% - 8%, drop in V_{OC}. These effects are due to the energetic protons found in LEO.

- The decrease in V_{OC} and I_{SC} for cell ISC#77 is greater than that of ISC#76 due to the shallower depth of its junction (0.35μm versus 0.50μm).

- There are no data regarding the effects of sub-micrometer to micrometer size M&D particles affecting cell performance as a result of junction penetration.

Experiment S0014 System-Level Effects Summary

CTM Contamination was present to a varying degree across the APEX, the thickness (not defined) being dependent on location. No loss of cell coverglass nor significant changes in color or appearance occurred. It is possible that contamination films can modify the anti-reflective properties of the coversheet front surface both positively and negatively.

MD M&D damage varied from micrometer-scale craters in coversheet surfaces to complete penetration (millimeter-scale) of an SCA through coversheet and cell to the aluminum faceplate. Some SCAs experienced coversheet perforation leading to cratering in the cell, but although cell cracking occurred electrical continuity was maintained. Loss in I_{SC} proportional to the damage area and decrease in FF due to cell cracking (increase in series resistance) was observed. Where coversheet perforation occurs significant degradation in electrical performance can be expected either from series resistance increases or p-n junction shunt resistance decrease.

AO Severe atomic oxygen erosion of silver ribbon (3 mil thick), used to connect cell front and back contacts to terminals mounted on the rear of the aluminum faceplate (via insulated feedthroughs), resulted in open circuits for SIX (6) SCAs. Erosion only occurred where the ribbon surface was face-on to the AO RAM direction. Where the ribbon was edge-on to the AO RAM direction minimal erosion occurred. Cell performance was not affected by erosion during the first 325 days on-orbit, implying that the erosion occurred primarily at lower altitude during the latter part of the mission.

RAD Unglassed cells suffered significant degradation in I_{SC} and V_{OC} parameters due to energetic proton bombardment. The better radiation hardness of higher base resistivity cells was confirmed. Radiation hardness is a function of junction depth with shallower-buried junctions being more susceptible to radiation damage than deeper-buried junctions.

UV There was negligible UV-induced darkening of either coversheets or adhesives. Reduction in I_{SC} for covered cells amounted to no more than 2.1% for silicon cells. The 12.2% reduction in I_{SC} for the single covered gallium arsenide cell characterized to date is not explained.

LDEF Location: **A08**

Experiment Identification: **A0171**

Experiment Title: **Solar Array Materials Passive LDEF Experiment (SAMPLE)**

The Solar Array Materials Passive LDEF Experiment (ref. 7) contained approximately 100 materials and materials processes which address primarily solar array materials. The experiment objective was to determine the electrical, mechanical, and optical property changes induced by the combined space environments. The experiment was located in Bay A08, offset from the spacecraft flight vector by 38.1°. There were FOUR (4) sub-experiments relating directly to solar cell assemblies, provided by NASA Marshall Space Flight Center (MSFC), NASA Lewis Research Center (LeRC), NASA Goddard Space Flight Center (GSFC), and the Jet Propulsion Laboratory (JPL). Figure 9 is a schematic of the experiment layout showing the location of the various solar cell test articles. The various environmental exposures for ROW 8 are specified below;

Sun Hours:	9409.39	ESH	(day = 2106)
Full Spectrum Solar Fluence:	4.63e+6	$J.cm^{-2}$	
UV Radiation (0.2-0.4μm):	3.69e+5	$J.cm^{-2}$	
AO Fluence:	6.93e+21	$atoms.cm^{-2}$	
Proton Fluence (0.05-200MeV):	1e+9	$protons.cm^{-2}$	
Electron Fluence (0.05-3.0MeV):	(1000-0.1)e+9	$electrons.cm^{-2}$	
Meteoroid & Debris (F-0.5mm):	7.0±0.6	$m^{-2}.yr^{-1}$	

It should be noted that part of the GSFC test plate was partially shielded from the RAM direction (spacecraft flight vector) since the experiment was in a 3" deep tray. Therefore, both the atomic oxygen and M&D fluences are not uniform across the surface of the test plate.

MSFC Test Plate

The MSFC sub-experiment comprised FOUR (4) solar cell modules and FIVE (5) individual solar cells. The modules were mounted over a double layer Kapton-H® flexible insulating substrate, with integral current-carrying copper interconnects, which was severely eroded by atomic oxygen during the mission. As a result, TWO (2) modules were lost, ONE (1), module M3, was partially detached, becoming fully detached during post-retrieval operations, and ONE (1), module M4, remained fully attached. Post-flight inspection of module M3 showed that 5 of the 12 SCAs comprising the module had suffered severe cracking of either the cells or the coversheets. This was apparently due to the fact that the module was loose in the Shuttle payload bay during re-entry and landing operations. Data pertaining to the lost modules are not presented here.

MSFC Solar Cell Modules

M4 6-cell module

CELLS	ASEC 2 mil (51μm) thick 2cm X 4cm Silicon n-on-p BSF (P^+) cells; base resistivity 10Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8μm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect.				
COVERS	TWO (2) Pilkington 2 mil (51μm) thick 4.7cm X 6.7cm microsheets per cell; cover/cell and cover/cover adhesive Dow-Corning DC93-500.				
CONFIGURATION	front surface of module space-facing.				
M&D damage:	Single large (millimeter-scale) impact caused extensive cracking in one cover.				
pre-FLT:	I_{SC} = 0.3233A	V_{OC} = 3.5527V	I_{MP} = 0.3010A	V_{MP} = 2.9132V	FF = 76.3
post-FLT:	I_{SC} = 0.3055A	V_{OC} = 3.5970V	I_{MP} = 0.2815A	V_{MP} = 2.9550V	FF = 75.7
Δ_parameter:	-5.5%	+1.2%	-6.5%	+1.4%	-0.6pct
ΔP_{MAX}:	-5.1%				

M3 12-cell module <<FOUR (4) sub-modules in series each comprising 3-cells in parallel>>

CELLS	ASEC 8 mil (203μm) thick 2cm X 4cm Silicon n-on-p BSR (aluminum) cells; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8μm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect.				
COVERS	OCLI 6 mil (152μm) thick microsheet with UV filter and AR coating; cover-cell adhesive Dow-Corning DC93-500.				
CONFIGURATION	rear surface of module space-facing.				
M&D damage:	TWO (2) large (millimeter-scale) impact sites in cells PC1L and PC2R; perforation of Kapton substrate leading to damage at cell/cover interface.				
pre-FLT:	I_{SC} = 0.8904A	V_{OC} = 2.3280V	I_{MP} = 0.8385A	V_{MP} = 1.9320V	FF = 78.2
post-FLT:	I_{SC} = 0.5552A	V_{OC} = 2.2650V	I_{MP} = 0.4245A	V_{MP} = 1.7550V	FF = 59.2
Δ_parameter:	-37.5%	-2.7%	-49.4%	-9.2%	-19.0pct
ΔP_{MAX}:	-31.9%				

MSFC Individual Solar Cells

CELL ***C6***	ASEC 8 mil (203µm) thick 2cm X 4cm Silicon n-on-p BSR (aluminum) cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3µm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8µm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect; NO cover; front surface of cell space-facing.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.2890A	V_{OC} = 0.5850V	I_{MP} =0.2682A	V_{MP} = 0.4855V	FF = 77.0
post-FLT:	I_{SC} = 0.2625A	V_{OC} = 0.5336V	I_{MP} = 0.2390A	V_{MP} = 0.4316V	FF = 73.6
Δ_parameter:	-9.2%	-8.8%	-10.9%	-11.1%	-3.4pct
ΔP_{MAX}:	--20.7%				

CELL ***C7***	ASEC 8 mil (203µm) thick 2cm X 4cm Silicon n-on-p BSR (aluminum) cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3µm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8µm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect; OCLI 6 mil (152µm) microsheet cover; with AR coating; front surface of cell space-facing.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.3068A	V_{OC} = 0.5825V	I_{MP} =0.2778A	V_{MP} = 0.4835V	FF = 75.2
post-FLT:	I_{SC} = 0.2927A	V_{OC} = 0.5824V	I_{MP} = 0.2667A	V_{MP} = 0.4768V	FF = 74.6
Δ_parameter:	-4.6%	-0.0%	-4.0%	-1.4%	-0.6pct
ΔP_{MAX}:	-5.3%				

CELL ***C8***	ASEC 8 mil (203µm) thick 2cm X 4cm Silicon n-on-p BSR (aluminum) cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3µm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8µm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect; OCLI 6 mil (152µm) microsheet cover; with AR coating and UV filter; front surface of cell space-facing.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF = 78.2
post-FLT:	I_{SC} = 0.2876A	V_{OC} = 0.5831V	I_{MP} = 0.2664A	V_{MP} = 0.4849V	FF = 77.0
Δ_parameter:	-3.1%	+0.2	-4.7%	+0.4%	-1.2pct
ΔP_{MAX}:	-4.3%				

CELL ***C9***	ASEC 8 mil (203μm) thick 2cm X 4cm Silicon n-on-p BSR (aluminum) cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8μm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect; OCLI 6 mil (152μm) frosted fused silica (SiO_2) cover; with AR coating and UV filter; front surface of cell space-facing.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.3000A	V_{OC} = 0.5820V	I_{MP} = 0.2753A	V_{MP} = 0.4889V	FF = 77.1
post-FLT:	I_{SC} = 0.2880A	V_{OC} = 0.5821V	I_{MP} = 0.2620A	V_{MP} = 0.4840V	FF = 75.6
Δ_parameter:	-4.0%	+0.0%	-4.8%	-1.0%	-1.5pct
ΔP_{MAX}:	-5.6%				

CELL ***C10***	ASEC 8 mil (203μm) thick 2cm X 4cm Silicon n-on-p BSR (aluminum) cell; base resistivity 2Ω.cm; junction depth (D_j) ~0.3μm; CVD dielectric for side wrap-around contacts; metalization Ti:Pd:Ag; contact thickness 4-8μm; dual AR coating; surface finish n/d; Kapton-H® substrate with integral Copper interconnect; OCLI 6 mil (152μm) fused silica (SiO_2) cover; with AR coating and UV filter; front surface of cell space-facing.				
M&D damage:	n/d				
pre-FLT:	I_{SC} = 0.3098A	V_{OC} = 0.5876V	I_{MP} = 0.2786A	V_{MP} = 0.4819V	FF = 73.8
post-FLT:	I_{SC} = 0.2932A	V_{OC} = 0.5875V	I_{MP} = 0.2669A	V_{MP} = 0.4764V	FF = 73.8
Δ_parameter:	-5.4%	-0.0%	-4.2%	-1.1%	-0.0pct
ΔP_{MAX}:	-5.3%				

MSFC Individual Sub-Modules & Cells Broken-Out From Modules

PC1 sub-module	<for SCA configuration see M3 module data panel>				
M&D damage:	cell PC1L experienced ONE (1) large (millimeter-scale) impact site; perforation of Kapton substrate leading to damage at cell/cover interface.				
pre-FLT:	I_{SC} = 0.8904A	V_{OC} = 0.5820V	I_{MP} = 0.8385A	V_{MP} = 0.4831V	FF = 78.2
post-FLT:	I_{SC} = 0.8782A	V_{OC} = 0.5795V	I_{MP} = 0.7877A	V_{MP} = 0.4690V	FF = 52.5
Δ_parameter:	-1.4%	-0.4%	-6.1%	-2.9%	-25.7pct
ΔP_{MAX}:	-8.8%				

PC2 sub-module	<for SCA configuration see M3 module data panel>				
M&D damage:	cell PC2R experienced ONE (1) large (millimeter-scale) impact site; perforation of Kapton substrate leading to damage at cell/cover interface.				
pre-FLT:	I_{SC} = 0.8904A	V_{OC} = 0.5820V	I_{MP} = 0.8385A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.7647A	V_{OC} = 0.5768V	I_{MP} = 0.5697A	V_{MP} = 0.4485V	FF = 57.9
Δ_parameter:	-14.1%	-0.9%	-32.1%	-7.2%	-20.3pct
ΔP_{MAX}:	-36.9%				

PC3 sub-module	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.8904A	V_{OC} = 0.5820V	I_{MP} = 0.8385A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.7843A	V_{OC} = 0.5788V	I_{MP} = 0.5355A	V_{MP} = 0.3969V	FF =46.8
Δ_parameter:	-11.9%	-0.5%	-36.1%	-17.8%	-31.4pct
ΔP_{MAX}:	-47.5%				

PC4 sub-module	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.8904A	V_{OC} = 0.5820V	I_{MP} = 0.8385A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.8714A	V_{OC} = 0.5784V	I_{MP} = 0.7945A	V_{MP} = 0.4546V	FF =71.7
Δ_parameter:	-2.1%	-0.6%	-5.2%	-5.9%	-6.5pct
ΔP_{MAX}:	-10.8%				

PC1L cell	<for SCA configuration see M3 module data panel>				
M&D damage:	ONE (1) large (millimeter-scale) impact site; perforation of Kapton substrate leading to damage at cell/cover interface.				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2928A	V_{OC} = 0.5843V	I_{MP} = 0.2665A	V_{MP} = 0.4591V	FF =71.5
Δ_parameter:	-1.3%	-0.4%	-4.7%	-5.0%	-6.7pct
ΔP_{MAX}:	-9.3%				

PC1C cell	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2931A	V_{OC} = 0.5800V	I_{MP} = 0.2697A	V_{MP} = 0.4774V	FF =75.7
Δ_parameter:	-1.2%	-0.3%	-3.5%	-1.2%	-2.5pct
ΔP_{MAX}:	-4.6%				

PC1R cell	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2945A	V_{OC} = 0.5856V	I_{MP} = 0.2640A	V_{MP} = 0.4765V	FF =72.9
Δ_parameter:	-0.8%	+0.6%	-5.5%	-0.7%	-5.3pct
ΔP_{MAX}:	-6.8%				

PC2L cell	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2925A	V_{OC} = 0.5834V	I_{MP} = 0.2661A	V_{MP} = 0.4574V	FF =71.3
Δ_parameter:	-1.4%	-0.2%	-4.8%	-5.3%	-6.9pct
ΔP_{MAX}:	-9.9%				

PC2C cell	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.1804A	V_{OC} = 0.5816V	I_{MP} = 0.0931A	V_{MP} = 0.2896V	FF =25.7
Δ_parameter:	-39.2%	-0.1%	-66.7%	-40.1%	-52.5pct
ΔP_{MAX}:	-80.0%				
	Significant material loss on wrap-around metalization due to AO resulting in significant increase in series resistance (0.007Ω -> 2.78Ω).				

PC2R cell	<for SCA configuration see M3 module data panel>				
M&D damage:	ONE (1) large (millimeter-scale) impact site; perforation of Kapton substrate leading to damage at cell/cover interface.				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2871A	V_{OC} = 0.5812V	I_{MP} = 0.2628A	V_{MP} = 0.4751V	FF =74.8
Δ_parameter:	-3.3%	-0.1%	-6.0%	-1.7%	-3.4pct
ΔP_{MAX}:	-7.6%				

PC3L cell	<for SCA configuration see M3 module data panel>				
M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2076A	V_{OC} = 0.5726V	I_{MP} = 0.1018A	V_{MP} = 0.3025V	FF =25.9
Δ_parameter:	-30.1%	-1.6%	-63.6%	-37.4%	-52.3pct
ΔP_{MAX}:	-77.2%				

PC3C cell <for SCA configuration see M3 module data panel>

M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2945A	V_{OC} = 0.5782V	I_{MP} = 0.2467A	V_{MP} = 0.3383V	FF =49.0
Δ_parameter:	-0.8%	-0.7%	-11.7%	-30.0%	-29.2pct
ΔP_{MAX}:	-38.2%				

PC3R cell <for SCA configuration see M3 module data panel>

M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2863A	V_{OC} = 0.5840V	I_{MP} = 0.2652A	V_{MP} = 0.4809V	FF =76.3
Δ_parameter:	-3.5%	+0.3%	-5.1%	-0.5%	-1.9pct
ΔP_{MAX}:	-5.6%				

PC4L cell <for SCA configuration see M3 module data panel>

M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2894A	V_{OC} = 0.5775V	I_{MP} = 0.2633A	V_{MP} = 0.4686V	FF =73.8
Δ_parameter:	-2.5%	-0.8%	-5.8%	-3.0%	-4.4pct
ΔP_{MAX}:	-8.6%				

PC4C cell <for SCA configuration see M3 module data panel>

M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2936A	V_{OC} = 0.5831V	I_{MP} = 0.2672A	V_{MP} = 0.4783V	FF =74.7
Δ_parameter:	-1.1%	+0.2%	-4.4%	-1.0%	-3.5pct
ΔP_{MAX}:	-5.3%				

PC4R cell <for SCA configuration see M3 module data panel>

M&D damage:	not significant				
pre-FLT:	I_{SC} = 0.2968A	V_{OC} = 0.5820V	I_{MP} = 0.2795A	V_{MP} = 0.4831V	FF =78.2
post-FLT:	I_{SC} = 0.2950A	V_{OC} = 0.5804V	I_{MP} = 0.2688A	V_{MP} = 0.4719V	FF =74.1
Δ_parameter:	-0.6%	-0.3%	-3.8%	-2.3%	-4.1pct
ΔP_{MAX}:	-6.1%				

Summary of M3 Modules Results

- The M3 module suffered a 31.9% degradation in P_{MAX}. Reduction in I_{SC} was 37.5%, but V_{OC} degraded only 2.7%, with *FF* being reduced from 78.2 to 59.2.

- Degradation in P_{MAX} for the individual cells ranged from 4.6% to 80%, with I-V data indicating a dramatic increase in R_S for the most severely degraded cells. There are indications of decreased shunt resistance in some cells (evidenced by a reduction in V_{OC}).

- The Kapton-H® substrate was eroded such that holes and/or cracks existed that allowed erosion of the silver back-surface metalization and wrap-around contacts. There was a high rate of mass loss in the wrap-around metalization. Electrical resistances of the wrap-arounds were found to be high. Cell PC2C showed a wrap-around resistance of 2.78Ω. Wrap-around resistance of a similar control cell was 0.007Ω. The degree of material degradation is proportional to the series resistance increase.

- M&D impact cratering (cells PC1L and PC2R) caused a 2% to 4% degradation in P_{MAX}. Craters smaller than 100μm diameter cause relatively small performance degradation. Small craters on the cell covers (i.e. non-perforating impacts) caused no discernible performance degradation.

Summary of M4 Module Results

- The M4 module suffered a 5.1% reduction in P_{MAX}. Reduction in I_{SC} was 5.5%, with V_{OC} and *FF* being unchanged within the bounds of experimental error.

Summary of Single Cell Results

- Changes in cover light transmission performance for Cells 7 through 10 were not discernible from electrical performance measurements.

- A 20.7% degradation in P_{MAX} experienced by Cell 6, which had no cover, was attributed to charged particle radiation damage, equivalent to a 1MeV mission fluence of 5e14 cm^{-2}.

Summary of Cell-to-Interconnect Bonding

- Cell-to-interconnect bonds were made by parallel-gap welding of the rolled-annealed Cu interconnects to the cell back surface Ag metalization.

- All cells had wrap-around contacts, allowing both bonds (from N- and P- contacts) to be made on the same side of the cells.

- Bonds were subjected to ~32,000 thermal cycles within the range -85°C to +80°C. There were no failed bonds found post-flight.

Experiment A0171-MSFC System-Level Effects Summary

CTM Contamination was present to a varying degree across A0171-MSFC, the thickness (not defined) being dependent on location. One localized area, where material outgassing occurred due to insufficient pre-flight thermal vacuum bake-out, was particularly badly contaminated. No loss of cell coverglass nor significant changes in color or appearance occurred.

MD M&D damage varied from micrometer-scale craters in coversheet surfaces to complete penetration (millimeter-scale) of SCAs through coversheet and cell. Currently, there are no data relating M&D damage to SCA performance degradation, although the cells with significant M&D damage (PC1L and PC2R) experienced very little degradation in electrical performance.

AO Severe atomic oxygen (AO) erosion of the double-layer Kapton-H® substrates occurred leading to the loss of TWO (2) modules in space. Severe erosion of some exposed wrap-around connections resulted in large increases in series resistance, resulting in significant reductions in FF and P_{MAX} for cells PC2C, PC3L, and PC3C.

RAD Unglassed cells suffered significant degradation in I_{SC} and V_{OC} parameters due to energetic proton bombardment.

UV There was negligible UV-induced darkening of either covers or adhesives. Reduction in I_{SC} for individual covered cells amounted to no more than 5.4% for 6mil (152µm) thick fused silica covers.

JPL Test Plate

The JPL test plate comprised THIRTY (30) SCAs (ref. 8). The cells were 50μm (2mil) thick 2cm X 2cm silicon solar cells manufactured by Solarex Corporation. Silver-plated invar tabs were welded to each cell to allow pre-flight and post-flight electrical performance measurements to be made. Each cell and tab assembly was bonded to a slightly oversize sheet of 25μm thick Kapton® insulation bonded to the aluminum baseplate. Bond materials were standard space-type silicone RTVs (e.g. DC93-500). Covers were bonded to the cells and included the folowing materials: ceria-doped microsheet, FEP Teflon®, Silicone (soft coat), Silicone (hard coat), BE-225HUP Polyimide-Silicone co-polymer, and GE X-76 Polyimide. The number of SCAs and combinations of covers/adhesives are listed below in Table 2 along with the average pre- and post-flight short circuit current $\langle I_{SC} \rangle$;

SCA Configuration	Cells	$\langle I_{SC} \rangle$ [pre-FLT]	$\langle I_{SC} \rangle$ [post-FLT]	$\langle \Delta I_{SC} \rangle$
100μm thick ceria-doped microsheet cover; inc. DC93-500 adhesive plus FOUR (4) other types (n/d)	6	136.5 mA	132.4 mA	-3%
50μm thick FEP Teflon cover; DC93-500 adhesive plus FOUR (4) other types (n/d)	10	136.8 mA	106.0 mA	-22%
12 - 75μm thick Silicone (soft coat) cover (inc. DC93-500)	6	132.0 mA	115.0 mA	-13%
12 - 75μm thick Silicone (hard coat) cover	4	135.o mA	112.0 mA	-17%
12 - 75μm thick GE X-76 Polyimide cover	2	129.5 mA	119.0 mA	-8%
12 - 75μm thick BE-225HUP Polyimide-Silicone co-polymer	2	125.0 mA	121.0 mA	-3%

Table 2. *Solar Cell Assembly cover types and electrical performance data for the 30 SCAs of the JPL test plate of experiment A0171 (ref. 8). No published data exists for V_{OC}, I_{MP}, V_{MP}, and FF.*

Summary of Ceria-Doped Microsheet Covers Results

- The SIX (6) cells using this type of cover , but with various silicone RTV adhesives, experienced on average a 3% degradation in I_{SC} after space exposure. This is attributed to radiation darkening of the microsheet cover and adhesive layer.

- No M&D damage sites, impact craters, were found that caused degradation in cell electrical performance (based solely on I_{SC} data, but not including V_{OC}, I_{MP}, V_{MP}, and FF).

Summary of Polymer Conformal Covers Results

- The BE-225HUP co-polymer covers suffered significant erosion with large areas of the cover being removed, exposing the cell to the AO and radiation environments directly. Similarly, the GE X-76 Polyimide covers were extensively removed.

- Hard-coat Silicone covers exhibited some coating loss (magnitude n/d) and significant upper surface "crazing." Soft-coat Silicone covers suffered only minimal removal, this being near the cell corners only.

- Where covers were partially, significantly, or completely removed the cells underwent substantial radiation damage (energetic protons) resulting in a complete collapse of the I-V profile (ref. 9).

Summary of FEP Teflon Covers Results

- I_{SC} losses varied from -10% to -43% for FEP Teflon covered cells.

- In one case the FEP Teflon cover was completely removed, leaving only a layer of Silicone RTV adhesive. The mechanism for removal is unknown. I_{SC} loss for this cell was -10%.

- M&D impacts in FEP Teflon readily penetrate the cover and damage the cell, lifting the FEP Teflon layer away from the cell. FEP Teflon provides negligible protection against hypervelocity impacts.

- The electrical performance characteristics (i.e. I_{SC}) of an SCA with a cover penetrating impact site were not noticeably different from other similarly covered cells. Other electrical performance parameters are not available. The impact site studied here resulted in complete penetration of the solar cell to the aluminum substrate.

- The I-V profiles for FEP Teflon covered cells did not undergo such significant degradation as those of the polymer-covered cells, indicating a continuing level of radiation protection. Reduction in I_{SC} can, therefore, be attributed mainly to UV-induced darkening of the covers.

- The cover surfaces appeared "charred" exhibiting a brown-gray color. Cell contact gridlines were visible as yellow-brown lines.

Experiment A0171-JPL System-Level Effects Summary

CTM Contamination levels are not defined at present. Brown-orange stains appeared around SCAs, indicating deposition of silicone adhesive and/or encapsulant residues derived from the samples.

MD M&D damage varied from micrometer-scale craters in cover surfaces to complete penetration (millimeter-scale) of SCAs through coversheet and cell. Currently, there are no data relating M&D damage to SCA performance degradation. There is no evidence, currently, that M&D impacts caused any electrical degradation in SCA performance.

AO Atomic oxygen (AO) erosion of silver-coated invar tabs. Tabs darkened (visual inspection) and showed signs of stress by the formation of platelets. In some areas the silver coating was fully eroded, exposing the invar substrate. Initial coating thickness was 4-6μm. FEP Teflon coatings appeared "charred" with a brown-gray color. Exposed cell contact gridlines experienced oxidation and some degree of flake-off (due to thermal cycling stresses) (ref. 9).

RAD Cells which lost their covers due to space environmental effects suffered upto 17% reduction in I_{SC} (complete removal of hard-coat Silicone), while significant removal (GE X-76 Polyimide) resulted in ~8% I_{SC} reduction and partial removal (BE-225HUP co-polymer) resulted in ~3% I_{SC} reduction. No V_{OC}, I_{MP}, V_{MP}, and FF data have been published

UV There was negligible UV-induced darkening of either covers or adhesives. Reduction in I_{SC} for individual microsheet covered cells amounted to an average of 3% for 100μm (4mil) thick covers. UV darkening probably affected the FEP Teflon covers significantly, although some darkening may be due to AO.

LeRC Test Plate

There is NO data available for this module.

GSFC Test Plate

The GSFC test plate was designed to test the space environmental effects (radiation, atomic oxygen, thermal cycling, meteroid & debris) on conductively coated solar cell coversheets, various electrical bond materials, solar cell performance, and other materials properties where feasible. The test plate contained twenty-eight 2 cm X 2 cm silicon solar cells (S-type), 305 µm (12 mil) thick, with silicon monoxide (SiO) anti-reflection (AR) coatings, covered by 305 µm thick fused silica (SiO_2) coversheets with indium-tin-oxide - $(In_x{:}Sb_{1-x})_2O_3$ - conductive coatings, and fifteen 2 cm X 6 cm, 305 µm thick, silicon solar cells (LD-type) with tantalum pentoxide (Ta_2O_5) AR coatings, boron-doped back surface field (BSF), aluminum back surface mirror (BSM), covered by various thickness (6 mil, 12 mil, and 40 mil) fused silica coversheets with MgF_2 AR coatings and UV blocking filters. Figure 10 shows the layout of the test plate, indicating the electrical connection points. A complete materials list (as-built, as-flown), data sheets for S-type SCAs, and data sheets for LD-type SCAs are presented elsewhere (ref. 10).

The S-type cells (note that the type designation, S- and LD-, are project specific) were bonded to the experiment faceplate (epoxy board) using Dow-Corning adhesive 93-500. Electrical connections were made to the coversheet front face using a variety of solders or conductively-loaded adhesives, the objective of which was to determine the best method of providing electrical continuity to the front face of the solar cell coversheet. Therefore, the cell contacts, nominally titanium-palladium-silver (Ti:Pd:Ag), were irrelevant to this part of the experiment. No measurements of cell current-voltage characteristics were possible.

Four vapor-deposited metallic (material undefined) pads are located on the front surface of each S-type cell coversheet, one in each corner. Pad-to-pad measurements of electrical resistance allows the surface coating resistivity to be characterized both pre- and post-flight. Each cell also has four electrical bond pads (EBPs) connected to terminal posts via 24-AWG copper (Cu) wire of either unplated or tin (Sb) plated type. Space environmental exposure of the various EBP materials was expected to modify or degrade the resistivity of the material. Terminal-to-pad measurements of resistance can indicate the relative degree of degradation, although due to the irregular nature of each EBP no estimate of resistivity could be obtained from such data.

The LD-type cells were bonded to the experiment faceplate using Dow-Corning adhesive 93-500. Cell electrical connections to terminal posts were made via Ti:Pd:Ag contacts to silver (Ag) mesh busbars which were mostly encapsulated in the 93-500 RTV silicone adhesive, except for those areas close to the terminal posts where the mesh was cut and twisted to make a connecting "wire" for soldering to the terminal itself. Covers of various thicknesses were bonded to the cells using 93-500 adhesive. Two of the 40 mil (1.02 mm) thick coversheets on SCAs LD-11 and LD-14 did not have the UV blocking filter that was applied to the other LD-type cell coversheets. The UV filter geometry (*e.g.* multi-layer) and material is undefined and so too is the 50% transmission cut-on wavelength.

These stacks were configured to allow electrical characterization of each cell. Pre-flight measurements of open circuit voltage (V_{OC}), short circuit current (I_{SC}), and maximum power (P_{MAX}) were made for AM0 conditions at an unspecified (although estimated at 25-28°C) temperature. Post-flight measurements of the same parameters were made by NASA GSFC personnel, again at an undefined temperature. Further post-flight complete electrical characterizations of the cells (including efficiency and fill factor) were made by Auburn University and NASA LeRC personnel.

GSFC 2cm X 6cm Silicon Solar Cells

CELL ***LD-1***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; NO cover.				
M&D damage:	25 sites; 19μm < D_S < 152μm; <D_S> = 61μm; SD = 35μm.				
pre-FLT:	I_{SC} = 0.495A	V_{OC} = 0.580V	I_{MP} = n/d	V_{MP} = n/d	FF = 74.9
post-FLT:	I_{SC} = 0.469A	V_{OC} = 0.454V	I_{MP} = n/d	V_{MP} = n/d	FF = 52.6
Δ_parameter:	-5.3%	-21.7%	n/d	n/d	-22.3pct
ΔP_{MAX}:	-47.9%				

CELL ***LD-2***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 12 mil (305μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	4 sites; 72μm < D_S < 165μm; <D_S> = 105μm; SD = 42μm.				
pre-FLT:	I_{SC} = 0.507A	V_{OC} = 0.595V	I_{MP} = n/d	V_{MP} = n/d	FF = 72.3
post-FLT:	I_{SC} = 0.509A	V_{OC} = 0.580V	I_{MP} = n/d	V_{MP} = n/d	FF = 71.5
Δ_parameter:	+0.4%	-2.5%	n/d	n/d	-0.8pct
ΔP_{MAX}:	-3.2%				

CELL ***LD-3***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 6 mil (152μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	5 sites; 95μm < D_S < 542μm; <D_S> = 256μm; SD = 187μm.				
pre-FLT:	I_{SC} = 0.503A	V_{OC} = 0.591V	I_{MP} = n/d	V_{MP} = n/d	FF = 74.0
post-FLT:	I_{SC} = 0.506A	V_{OC} = 0.578V	I_{MP} = n/d	V_{MP} = n/d	FF = 73.2
Δ_parameter:	+0.6%	-2.2%	n/d	n/d	-0.8pct
ΔP_{MAX}:	-2.7%				

CELL ***LD-4***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; NO cover				
M&D damage:	27 sites; 20μm < D_S < 130μm; $\langle D_S \rangle$ = 51μm; SD = 25μm.				
pre-FLT:	I_{SC} = 0.497A	V_{OC} = 0.592V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.1
post-FLT:	I_{SC} = 0.465A	V_{OC} = 0.452V	I_{MP} = n/d	V_{MP} = n/d	FF = 66.1
Δ_parameter:	-6.4%	-23.6%	n/d	n/d	-9.0pct
ΔP_{MAX}:	-37.1%				

CELL ***LD-5***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 40 mil (1.02mm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	5 sites; 61μm < D_S < 93μm; $\langle D_S \rangle$ = 141μm; SD = 93μm.				
pre-FLT:	I_{SC} = 0.511A	V_{OC} = 0.594V	I_{MP} = n/d	V_{MP} = n/d	FF = 72.5
post-FLT:	I_{SC} = 0.507A	V_{OC} = 0.578V	I_{MP} = n/d	V_{MP} = n/d	FF = 72.0
Δ_parameter:	-0.8%	-2.7%	n/d	n/d	-0.5pct
ΔP_{MAX}:	-4.1%				

CELL ***LD-6***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 6 mil (152μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	15 sites; 43μm < D_S < 313μm; $\langle D_S \rangle$ = 120μm; SD = 72μm.				
pre-FLT:	I_{SC} = 0.507A	V_{OC} = 0.587V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.6
post-FLT:	I_{SC} = 0.507A	V_{OC} = 0.578V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.1
Δ_parameter:	-0.0%	-1.5%	n/d	n/d	-0.5pct
ΔP_{MAX}:	-2.2%				

CELL ***LD-7***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 6 mil (152μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	17 sites; 34μm < D_S < 310μm; $\langle D_S \rangle$ = 115μm; SD = 68μm.				
pre-FLT:	I_{SC} = 0.508A	V_{OC} = 0.577V	I_{MP} = n/d	V_{MP} = n/d	FF = 64.5
post-FLT:	I_{SC} = 0.511A	V_{OC} = 0.571V	I_{MP} = n/d	V_{MP} = n/d	FF = 64.4
Δ_parameter:	+0.6%	-1.0%	n/d	n/d	-0.1pct
ΔP_{MAX}:	-0.5%				

CELL ***LD-8***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 40 mil (1.02mm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	8 sites; $45\mu m < D_S < 344\mu m$; $\langle D_S \rangle = 123\mu m$; SD = 94μm.				
pre-FLT:	I_{SC} = 0.516A	V_{OC} = 0.586V	I_{MP} = n/d	V_{MP} = n/d	FF = 74.4
post-FLT:	I_{SC} = 0.510A	V_{OC} = 0.574V	I_{MP} = n/d	V_{MP} = n/d	FF = 74.5
Δ_parameter:	-1.2%	-2.0%	n/d	n/d	+0.1pct
ΔP_{MAX}:	-3.1%				

CELL ***LD-9***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 12 mil (305μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	12 sites; $74\mu m < D_S < 787\mu m$; $\langle D_S \rangle = 212\mu m$; SD = 202μm.				
pre-FLT:	I_{SC} = 0.508A	V_{OC} = 0.577V	I_{MP} = n/d	V_{MP} = n/d	FF = 68.2
post-FLT:	I_{SC} = 0.502A	V_{OC} = 0.569V	I_{MP} = n/d	V_{MP} = n/d	FF = 69.0
Δ_parameter:	-1.2%	-1.4%	n/d	n/d	+0.8pct
ΔP_{MAX}:	-0.2%				

CELL ***LD-10***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 6 mil (152μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	15 sites; $34\mu m < D_S < 129\mu m$; $\langle D_S \rangle = 63\mu m$; SD = 26μm.				
pre-FLT:	I_{SC} = 0.505A	V_{OC} = 0.584V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.6
post-FLT:	I_{SC} = 0.505A	V_{OC} = 0.573V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.3
Δ_parameter:	-0.0%	-1.9%	n/d	n/d	-0.3pct
ΔP_{MAX}:	-2.2%				

CELL ***LD-11***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 40 mil (1.02mm) fused silica (SiO_2) cover; MgF_2 AR coating.				
M&D damage:	12 sites; $61\mu m < D_S < 272\mu m$; $\langle D_S \rangle = 134\mu m$; SD = 64μm.				
pre-FLT:	I_{SC} = 0.519A	V_{OC} = 0.593V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.7
post-FLT:	I_{SC} = 0.514A	V_{OC} = 0.582V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.9
Δ_parameter:	-1.0%	-1.9%	n/d	n/d	+0.2pct
ΔP_{MAX}:	-2.6%				

CELL ***LD-12***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 40 mil (1.02mm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	15 sites; 60μm < D_S < 910μm; <D_S> = 235μm; SD = 261μm.				
pre-FLT:	I_{SC} = 0.521A	V_{OC} = 0.591V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.0
post-FLT:	I_{SC} = 0.514A	V_{OC} = 0.579V	I_{MP} = n/d	V_{MP} = n/d	FF = 74.9
Δ_parameter:	-1.3%	-2.0%	n/d	n/d	-0.1pct
ΔP_{MAX}:	-3.5%				

CELL ***LD-13***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 12 mil (305μm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	20 sites; 26μm < D_S < 210μm; <D_S> = 82μm; SD = 52μm.				
pre-FLT:	I_{SC} = 0.510A	V_{OC} = 0.585V	I_{MP} = n/d	V_{MP} = n/d	FF = 76.1
post-FLT:	I_{SC} = 0.505A	V_{OC} = 0.572V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.8
Δ_parameter:	-1.0%	-2.2%	n/d	n/d	-0.3pct
ΔP_{MAX}:	-3.5%				

CELL ***LD-14***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 40 mil (1.02mm) fused silica (SiO_2) cover; MgF_2 AR coating.				
M&D damage:	10 sites; 68μm < D_S < 187μm; <D_S> = 103μm; SD = 40μm.				
pre-FLT:	I_{SC} = 0.521A	V_{OC} = 0.591V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.0
post-FLT:	I_{SC} = 0.509A	V_{OC} = 0.579V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.0
Δ_parameter:	-2.3%	-2.0%	n/d	n/d	-0.0pct
ΔP_{MAX}:	-4.3%				

CELL ***LD-15***	Spectrolab 12 mil (305μm) thick 2cm X 6cm K-6.5 Silicon n-on-p BSR cell; base resistivity n/d; junction depth n/d; metalization Ti:Pd:Ag; Ta_2O_5 AR coating; surface finish n/d; glass-fiber/epoxy matrix substrate; 40 mil (1.02mm) fused silica (SiO_2) cover; MgF_2 AR coating; UV filter.				
M&D damage:	7 sites; 61μm < D_S < 149μm; <D_S> = 100μm; SD = 32μm.				
pre-FLT:	I_{SC} = 0.521A	V_{OC} = 0.584V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.3
post-FLT:	I_{SC} = 0.512A	V_{OC} = 0.577V	I_{MP} = n/d	V_{MP} = n/d	FF = 75.5
Δ_parameter:	-1.7%	-1.2%	n/d	n/d	+0.2pct
ΔP_{MAX}:	-2.6%				

GSFC Indium-Tin-Oxide SCA Cover Conductive Coatings

The twenty-eight (28) S-type cell assemblies were constructed to allow measurements of the indium-tin-oxide cover coating electrical resistance. Derived statistical data are presented below (see ref.10). ROW numbers refer, in this case, to the rows of SCAs on the GSFC test plate, only (see figure 10).

	pre-FLT-GSFC [kΩ]	post-FLT-GSFC [kΩ]	post-FLT-AU [kΩ]
MIN	3.2	4.1	4.1
MAX	9.6	35.2	32.3
Mean	5.1	11.4	11.0
SD	1.8	6.6	6.0
Std Error	0.3	1.3	1.2

Table 3. *Statistical resistance data for 28 S-type silicon solar cell assemblies with indium tin-oxide conductive coatings on the front of the fused silica (SiO_2) covers.*

	$\langle R_{PP}\rangle$[kΩ]	σ_{PP} [kΩ]	$\langle R_{post}/R_{pre}\rangle$	$\sigma_{R_{post}/R_{pre}}$
ROW-5	6.39	1.41	1.09	0.23
ROWS 1-4	4.59	2.41	2.75	1.12

Table 4. *$\langle R_{PP}\rangle$= mean pad-to-pad resistance; σ_{PP} = pad-to-pad resistance standard deviation; $\langle R_{post}/R_{pre}\rangle$ = mean of post-flight-to-pre-flight resistance ratios; $\sigma_{R_{post}/R_{pre}}$= standard deviation of post-flight-to-pre-flight resistance ratios.*

GSFC EBP Conductive Bond Materials

Each S-type cell has four EBPs attached to the coversheet front surface. Measurements of terminal-to-pad resistance for each of the EBPs was made to each of the two nearest pads. Estimated EBP resistance is computed by correcting for the surface coating resistance between the two pads adjacent to the EBP (ref. 10). Statistical data for the various bond material types are shown below:

bond-composition-plating	$\langle R\rangle$ [kΩ]	SD_n	$SD_n/\langle R\rangle$
Ecc56C-10%TOL-unPL	64±5	24.6	0.38
Ecc56C-10%ALC-unPL	46±4	18.5	0.40
Ecc56CH-10%TOL-unPL	51±4	24.0	0.47
EPON815-SnPL	20±4	15.4	0.75
SOLDR#1-50%In50%Sn-SnPL	0.28±0.01	0.05	0.18
SOLDR#3-90%In10%Sn-SnPL	0.21±0.01	0.05	0.24

Table 5. *Pre-flight EBP resistance data. $\langle R\rangle$ is the bond resistance averaged across all cells. SD_n is the standard deviation in the data. The variable $SD_n/\langle R\rangle$ is a relative measure of the spread in the data about the mean value of resistance.*

bond-composition-plating	<*R*> [kΩ]	<R_{post}>/<R_{pre}>	SD_n	SD_n/<*R*>
Ecc56C-10%TOL-unPL	3.2±0.6	0.05±0.01	2.7	0.84
Ecc56C-10%ALC-unPL	5±1	0.11±0.03	4.6	0.92
Ecc56CH-10%TOL-unPL	3.2±0.6	0.06±0.02	2.4	0.75
EPON815-SnPL	2.6±0.5	0.13±0.05	1.8	0.69
SOLDR#1-50%In50%Sn-SnPL	0.56±0.04	2.00±0.21	0.21	0.38
SOLDR#3-90%In10%Sn-SnPL	0.36±0.04	1.71±0.27	0.16	0.44

Table 6. *Post-flight EBP resistance data. as measured by NASA GSFC personnel (June 1992). <R> is the bond resistance averaged across all cells. SD_n is the standard deviation in the data. The variable SD_n / <R> is a relative measure of the spread in the data about the mean value of resistance. This data excludes all open circuit terminal-to-pad combinations.*

Note the following nomenclature: Ecc56C = Eccobond 56C Ag-loaded epoxy adhesive; TOL = toluene; ALC = alcohol; unPL = unplated; SnPL = tin plated; SOLDR = solder; In = indium; Sn = tin; EPON815 = Ag-loaded epoxy adhesive.

Summary of Silicon Solar Cell Results

- I_{SC} losses for covered cells were less than 2.3%. V_{OC} degradation for covered cells was no more than 2.7%. Post-flight degradation values of I_{SC} correlate with cover thickness, with thicker covers showing greater reduction in I_{SC}. For V_{OC}, there is no correlation between V_{OC} degradation and cover thickness.

- Uncovered cells suffered minimal reduction in I_{SC} (no more than 6.4%), but suffered major reductions in V_{OC} (down between 21.7% and 23.6%) and P_{MAX} (down between 37.1% and 47.9%). Front contact erosion by AO may have contributed to I-V profile degradation by increasing R_S.

- The presence of UV blocking filters produced no discernible or quantifiable effects.

Summary of ITO Conductive Coatings Results

- Indium oxide conductive coatings on solar cell coversheets are subject to degradation by the AO environment. The partially-shielded cells in ROW-5 exhibited little increase in coating resistance (~9% on average), whereas the fully-exposed cells in ROWs 1-4 exhibited an increase of ~175%.

- A further degradation mode was found whereby large M&D impacts (*e.g.* impact on cell S-10) cause surface cracking, leading to electrical isolation of parts of the coversheet surface. Such isolation can be restored mechanically by applying pressure to isolated areas bringing them back into contact with their surrounds implying that thermal cycling may cause intermittent restoration of electrical continuity also. There are implications for differential charging/ discharging occurrences where isolated areas become charged, being discharged when electrical continuity is restored.

Summary of EBP Conductive Bond Materials

- The electrical bond pads showed various levels of resistance changes. Typically, the resistance of the adhesive-based bond pads decreased, most probably due to outgassing, whereas the resistance of the solder-based bond pads typically increased, indicating thermally-induced stresses occured at the coversheet-EBP interface due to a greater thermal expansion mismatch.

Experiment A0171-GSFC System-Level Effects Summary

CTM Contamination levels are not defined at present.

MD M&D damage varied from micrometer-scale craters in cover surfaces to complete penetration (millimeter-scale) of SCAs through coversheet and cell on S-type SCAs. No total penetration sites were found on the LD-type SCAs. Currently, there are no data relating M&D damage to SCA performance degradation. There is no evidence, currently, that M&D impacts caused any electrical degradation in SCA performance. The effect of M&D penetrations in uncovered cells cannot be separated from the radiation damage effects.

AO Atomic oxygen (AO) erosion of uncovered cells (LD-1 and LD-4) silver gridlines (metalization) occurred extensively. AO damage to ITO conductive coatings was significant with such coatings exhibiting a ~175% increase in resistance.

RAD Uncovered cells suffered significant degradation in performance.

UV UV-induced darkening of either covers or adhesives occurred, although the resultant reduction in I_{SC} was limited to no more than 2.3%.

LDEF Location: D03 & D09

Experiment Identification: M0003-4

Experiment Title: Advanced Solar Cell and Coverglass Analysis

This experiment comprised 63 solar cell cover samples and 12 solar cell strings (refs 3 & 11). Sixteen (16) of the cover samples were on Row 09 (leading edge), offset from the spacecraft flight vector by 8.1°, 16 were on Row 03 (trailing edge), offset by 171.9°, and 16 were on the backside of a tray protected from direct exposure to the LEO environment. An additional 15 samples were used as control samples and were not flown. These elements were exposed to the following space environments:

Bay D03

Sun Hours:	11110.07	ESH	(day = 2106)
Full Spectrum Solar Fluence:	5.47e+6	$J.cm^{-2}$	
UV Radiation (0.2-0.4μm):	4.36e+5	$J.cm^{-2}$	
AO Fluence:	1.32e+17	$atoms.cm^{-2}$	
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$	
Electron Fluence (0.05-3.0MeV):	TBD	$electrons.cm^{-2}$	
Meteoroid & Debris (F-0.5mm):	0.8±0.2	$m^{-2}.yr^{-1}$	

Bay D09

Sun Hours:	11155.87	ESH	(day = 2106)
Full Spectrum Solar Fluence:	5.49e+6	$J.cm^{-2}$	
UV Radiation (0.2-0.4μm):	4.38e+5	$J.cm^{-2}$	
AO Fluence:	8.72e+21	$atoms.cm^{-2}$	
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$	
Electron Fluence (0.05-3.0MeV):	TBD	$electrons.cm^{-2}$	
Meteoroid & Debris (F-0.5mm):	7.9±0.6	$m^{-2}.yr^{-1}$	

<u>Summary of Solar Cell Results</u>

Currently, there are NO data relating to solar cells from this experiment.

<u>Summary of Solar Cell Cover Results</u>

- Cover samples were characterized by optical transmission, reflectance, and absorptance in their as-returned "dirty" condition.

- Surface contamination increases absorption by increasing the cut-on wavelength of the upper surface transmission profile. This effect was more significant for trailing edge samples than for leading edge samples. The principal investigators determined that AO provides a "scrubbing effect."

- Leading edge magnesium fluoride (MgF_2) samples contained fluorinated organic contaminants. Also, significant replacement of fluorine by oxygen ocurred.

- Leading edge thorium fluoride (ThF_4) samples suffered complete removal of fluorine. No oxide layer was detected.

- Leading edge fused silica (SiO_2) samples showed no change.

- Trailing edge samples were contaminated by a layer ~100Å thick composed mainly of silicon (Si), carbon (C), and oxygen (O). Approximately 50% of samples showed traces of nitrogen (N), fluorine (F), and tin (Sn). Silicone-based contamination was also present.

LDEF Location: **H01**

Experiment Identification: **S1001**

Experiment Title: **LDEF Heat Pipe Experiment Power Sub-system**

The LDEF Heat Pipe Experiment Power Sub-system comprised four solar arrays each with 68 2cm X 6cm silicon solar cells for a total of 272 cells (ref. 12). All cells were covered although the cover material is undefined. These arrays were flown for power generation purposes only, although I-V data are available. The exposure environment is specified below:

Sun Hours:	14547.04	ESH (day = 2106)
Full Spectrum Solar Fluence:	7.16e+6	$J.cm^{-2}$
UV Radiation (0.2-0.4μm):	5.71e+5	$J.cm^{-2}$
AO Fluence:	4.27e+20	$atoms.cm^{-2}$
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$
Electron Fluence (0.05-3.0MeV):	TBD	$electrons.cm^{-2}$
Meteoroid & Debris (F-0.5mm):	5.8±0.9	$m^{-2}.yr^{-1}$

<u>Summary of Silicon Solar Array Results</u>

- A total area of $3264cm^2$ was exposed. Ninety-nine (99) M&D impact sites were detected of which twenty-nine (29) caused cover glass cracks. Fifteen (15) additional coverglass cracks were found that could not be directly attributed to M&D impacts.

- Other damage and/or contamination effects include: one cell interconnect was damaged by an M&D impact; small area (diameter u/d) of burned residue (material u/d) on panel #223; small area (diameter u/d) of debris (material u/d) on panel #200; adhesive (type n/d) spread on panel edges; small traces of Apiezon-H bled into panel edges; Solithane (Morton-Thiokol) conformal coating of panel wiring and terminals was darkened after space exposure.

- I-V data from panel #132 indicate that there was a 1.5% reduction in I_{SC}, a 3.3% reduction in V_{OC}, and a 3.5% reduction in P_{MAX} after space exposure. Such data are typical of all four panels flown. An identical control sample (stored in a closed container at GSFC) showed a 0.27% reduction in I_{SC} and a 0.6% reduction in V_{OC}.

LDEF Location: E03

Experiment Identification: S1002

Experiment Title: **Evaluation of Thermal Control Coatings and Solar Cells**

The Evaluation of Thermal Control Coatings and Solar Cells experiment comprised a series of solar cells and related components contained within a standard experiment exposure control cannister (EECC) (ref. 13). As a result, the solar cell components under review here were exposed for only approximately NINE (9) months. The environment specified below is that for 270±10 days exposure.

Sun Hours:	1440±45	ESH (day = 270±10)
Full Spectrum Solar Fluence:	(7.1±0.2)e+5	$J.cm^{-2}$
UV Radiation (0.2-0.4μm):	(5.7±0.2)e+4	$J.cm^{-2}$
AO Fluence:	(1.7±0.2)e+16	$atoms.cm^{-2}$
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$
Electron Fluence (0.05-3.0MeV):	7.0e11	(1MeV equivalent) $electrons.cm^{-2}$
Meteoroid & Debris (F-0.5mm):	0.8±0.2	$m^{-2}.yr^{-1}$

This experiment examined the electrical performance characteristics of both Silicon solar cells and Indium Tin Oxide (ITO) conductive coatings: i.e. tin-doped indium oxide; $(In_X{:}Sb_{1-X})_2O_3$. Such coatings are deposited on the front surface of solar cell covers to provide electrical connectivity to bleed-off charge which would otherwise build-up due to the presence of the LEO ambient plasma environment. TWO (2) GEOS solar cell modules and ONE (1) OTS solar cell modules were exposed. SCA configurations are specified below. Electrical performance characteristics of ITO coatings and thermo-optical characteristics are specified in Tables 7 and 8, respectively.

Date	23-MAR-79	29-NOV-83	12-MAR-90	18-MAY-90	22-MAY-90	30-MAY-90
Conditions	ambient atmosphere	EECC closed: ambient atmosphere	EECC closed: vacuum	EECC closed: ambient atmosphere	ambient atmosphere	ambient atmosphere
Flight GEOS module 11	4.2	n/d	n/d	n/d	4.2	4.4
Flight GEOS module12	4.8	5.0	4.6	5.2	5.5	6.9
Control GEOS module 10	3.9	n/d	n/d	n/d	n/d	4.6
Control GEOS module 1	4.7	n/d	n/d	n/d	n/d	5.2

Table 7. *Electrical resistance measured in kilo-ohms (kΩ) of ITO surface coatings for GEOS flight and control samples under various pre- and post-flight environments.*

GEOS module	<<number of cells and configuration not defined>>				
CELLS	200μm (8mil) thick Silicon n-on-p cells; base resistivity 1Ω.cm; AR coating n/d; cell-substrate (Al) interface comprises 80μm RTV 566/DC1200, over 5μm. DP46971, over 25μm Kapton-H, over 5μm DP46971.				
COVERS	OCLI 300μm (12 mil) thick fused silica (SiO_2) cover with 200Å thick ITO coating; cover-cell adhesive XR6-3489 ~30μm thick.				
pre-FLT:	I_{SC} = 0.568A	V_{OC} = 0.606V	I_{MP} = 0.54A est.	V_{MP} = 0.5V est.	FF = n/a
post-FLT:	I_{SC} = 0.539A	V_{OC} = 0.600V	I_{MP} = 0.49A est.	V_{MP} = 0.5V est.	FF = n/a
Δ_parameter:	-5.1%%	-1.0%	-9.3%	-0.0%	n/a
ΔP_{MAX}:	-9.3%				

OTS module	<<number of cells and configuration not defined>>				
CELLS	200μm (8mil) thick Silicon n-on-p cells; base resistivity 1Ω.cm; AR coating n/d; cell-substrate (Al) interface comprises 80μm RTV 566/DC1200, over 5μm. DP46971, over 25μm Kapton-H, over 5μm DP46971.				
COVERS	Pilkington 300μm (12 mil) thick CMS microsheet; cover-cell adhesive Dow-Corning DC93-500 ~30μm thick.				
pre-FLT:	I_{SC} = 0.593A	V_{OC} = 0.611V	I_{MP} = 0.55A est.	V_{MP} = 0.51V est.	FF = n/a
post-FLT:	I_{SC} = 0.576A	V_{OC} = 0.602V	I_{MP} = 0.53A est.	V_{MP} = 0.51V est.	FF = n/a
Δ_parameter:	-2.9%%	-1.5%	-3.6%	-0.0%	n/a
ΔP_{MAX}:	-3.6%				

Component	α_S	$\Delta\alpha_S$	ε_H	$\Delta\varepsilon_H$
Flight OTS module 13	0.83±0.01	+1.0%	0.79±0.04	+0.0%
Control OTS module 5	0.82±0.01	+0.0%	0.79±0.04	+0.0%
Flight GEOS module 12	0.81±0.01	+0.0%	0.77±0.04	+0.0%
Flight GEOS module 11	0.81±0.01	+0.0%	0.77±0.04	+0.0%
Control GEOS module 10	0.81±0.01	+0.0%	0.77±0.04	+0.0%
Control GEOS module 1	0.81±0.01	+0.0%	0.77±0.04	+0.0%

Table 8. *Thermo-optical characteristics of the various flight and control solar cell modules. Note:* α_S *= solar absorptivity* ε_H *= hemispherical thermal emissivity.*

Summary of Solar Cell Module Results

- On each of the GEOS solar cell modules THREE (3) of the FOUR (4) interconnects were cracked, but electrical continuity was maintained. ONE (1) of the THREE (3) interconnect fingers on ONE (1) of the GEOS solar cells was cracked. ALL silver interconnects were darkened in color. The dark surface material was determined to be Silver Sulfide (Ag_2S).

- Surface resistance of the ITO conductive coatings on solar cell covers was found to be in the kΩ range.

- The GEOS solar cell modules experienced a 5.1% reduction in I_{SC}, a 1.0% reduction in V_{OC}, and an estimated 9.3% reduction in P_{MAX}. The OTS solar cell module experienced a 2.9% reduction in I_{SC}, a 1.5% reduction in V_{OC}, and an estimated 3.6% reduction in P_{MAX}.

- Microfractographical investigations of a broken loop solar cell interconnect of a GEOS module exhibited a series of fine, parallel grooves (oscillatory bands), indicating the advance of the delamination front under an oscillatory load, i.e. thermal cycle generated fatigue fracture. Note that the solar cells were bonded to an aluminum base structure, not a carbon-fiber faceplate over aluminum honeycomb structure as is usual for solar panels. Therefore, the interconnects underwent significantly higher mechanical loads due to the cell-baseplate thermal mis-match than would be typical under normal design practice.

Experiment S1002 System-Level Effects Summary

CTM Contamination does not influence thermal emissivity (ε_H), while solar absorptivity (α_S) is increased marginally for most components, although the SCAs experienced no increase in α_S typically. A contamination influence over the electrical conductivity of the ITO coatings could not be detected.

MD M&D damage varied from sub-micrometer-scale to millimeter-scale craters,although no significant damage to solar cell modules was found. There is no evidence that M&D impacts caused any electrical degradation in SCA performance.

AO Atomic oxygen erosion was insignificant.

RAD Radiation damage was insignificant.

UV UV-induced darkening of solar cell covers and adhesives was not detectable.

LDEF Location: **B04 & D10**

Experiment Identification: **A0054**

Experiment Title: **Space Plasma-High Voltage Drainage Experiment**

The Space Plasma-High Voltage Drainage Experiment (SP-HVDE) comprised two indentical experimental trays, one located in Bay D10 (near the leading edge, RAM-facing) and one in Bay B04 (near the trailing edge, WAKE-facing) (ref. 14). For the purposes of this report only the solar cell strings are considered. In each tray there were two solar cell strings, one biased at +300V and one at -300V, to study current leakage from high voltage solar arrays. Each cell module consisted in three solar cells in series with a load resistor. Each solar cell assembly (SCA) appears to comprise an oversize 2cm X 4cm single crystal silicon cell with a fused silica (SiO_2) coversheet. The coversheet and cell anti-reflection coatings are undefined. Cell thickness and coversheet thickness are undefined, too. The cells have a base resistivity of 10 Ω.cm.

Bay B04

Sun Hours:	10458.41	ESH (day = 2106)
Full Spectrum Solar Fluence:	5.15e+6	$J.cm^{-2}$
UV Radiation (0.2-0.4μm):	4.10e+5	$J.cm^{-2}$
AO Fluence:	9.32e+4	$atoms.cm^{-2}$
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$
Electron Fluence (0.05-3.0MeV):	TBD	$electrons.cm^{-2}$
Meteoroid & Debris (F-0.5mm):	0.7±0.2	$m^{-2}.yr^{-1}$

Bay D10

Sun Hours:	10697.80	ESH (day = 2106)
Full Spectrum Solar Fluence:	5.27e+6	$J.cm^{-2}$
UV Radiation (0.2-0.4μm):	4.20e+5	$J.cm^{-2}$
AO Fluence:	8.17e+21	$atoms.cm^{-2}$
Proton Fluence (0.05-200MeV):	TBD	$protons.cm^{-2}$
Electron Fluence (0.05-3.0MeV):	TBD	$electrons.cm^{-2}$
Meteoroid & Debris (F-0.5mm):	9.6±0.6	$m^{-2}.yr^{-1}$

Two control sample modules were maintained by TRW so that pre-flight and post-flight comparisons of module electrical performance could be made (ref. 14). One of the cells on a leading edge module experienced a meteroid or debris impact which caused significant structural damage. The impactor penetrated the coversheet and silicone adhesive, producing a raised and melted spall zone on the solar cell whose diameter was ~485-500μm. The coversheet was spalled out to a diameter of ~1.5mm. The cell itself was not penetrated through to the faceplate. Scanning electron microscopy (SEM) indicates that the damage zone in the cell has a diameter of ~200μm, implying that the cell junction has been penetrated, also. Damage to the SCA extends well beyond the immediate impact site with radial cracks in the coversheet extending ~5mm from the center of impact. Table 9 shows the electrical characteristics data for each 3-cell module.

Cell Module	V_{OC} [V]	I_{SC} [A]	V_{MP} [V]	I_{MP} [A]	P_{MAX}[W]	Comments
#1 Trailing (B4)	1.63	0.285	1.36	0.271	0.369	
#2 Trailing (B4)	1.63	0.286	1.36	0.272	0.370	
#3 Leading (D10)	1.63	0.290	1.36	0.272	0.369	
#4 Leading (D10)	1.64	0.223	1.51	0.222	0.336	M&D impact
#5 Control	1.64	0.287	1.37	0.275	0.377	
#6 Control	1.64	0.287	1.37	0.273	0.374	

Table 9. *Electrical characteristics of the six 3-cell modules.*

<u>Summary of Solar Cell Module Results</u>

- Assuming the two control samples accurately reflect the pre-flight characteristics of the four flight samples, it can be seen that V_{OC} is essentially unchanged (0.6% average reduction) and that the M&D impact caused no change in this parameter. Likewise, I_{SC} is not significantly changed for the undamaged modules (0.0% average reduction) nor is the maximum power much reduced (0.6% average reduction).

- The M&D impact-damaged module exhibits a 22.3% reduction in I_{SC} and a 10.5% reduction in P_{MAX} while V_{OC} is essentially unchanged. Further anomalous characteristics are evident from the fact that although I_{SC} has been reduced significantly the current at maximum power (I_{MP}) remains close in magnitude to the short-circuit current. Voltage at maximum power (V_{MP}) increases from 1.36V in the undamaged module to 1.51V in the damaged one. Figure 11 shows the pre- and post-flight performance of the damaged module, graphically.

- The structural damage to the SCA covers no more than 0.25% of the cell surface area, but module power reduction was 10.5% (including undamaged cell output) and the available current was reduced by ~22%. Therefore, mere aperture reduction due to M&D erosion is insignificant for SCAs while <u>penetration of the cell p-n junction is extremely damaging</u>.

Experiment A0054 System-Level Effects Summary

CTM Contamination data is not available.

MD M&D damage to one leading edge cell was detected. A millimeter-scale particle penetrated a cell cover, cratering the cell. Significant reduction in the 3-string module performance was observed.

AO Atomic oxygen erosion was insignificant.

RAD Radiation damage was insignificant.

UV UV-induced darkening of solar cell covers and adhesives was not detectable.

ACKNOWLEDGMENTS

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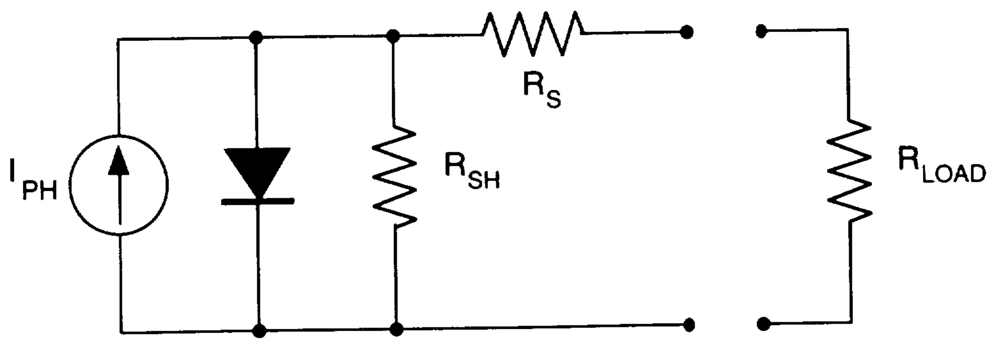

Figure 1. *Solar cell equivalent circuit.* I_{PH} *is the photo-current,* R_{SH} *is the shunt resistance,* R_S *is the series resistance, including cell and interconnect resistances.*

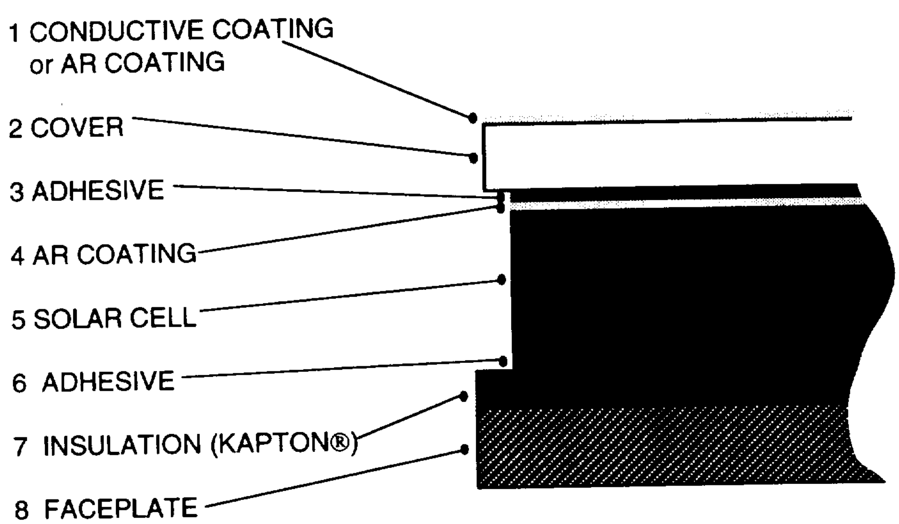

Figure 2. *Schematic cross-section of a typical solar cell assembly (SCA). Thicknesses are not drawn to scale. Note: AR = anti-reflection.*

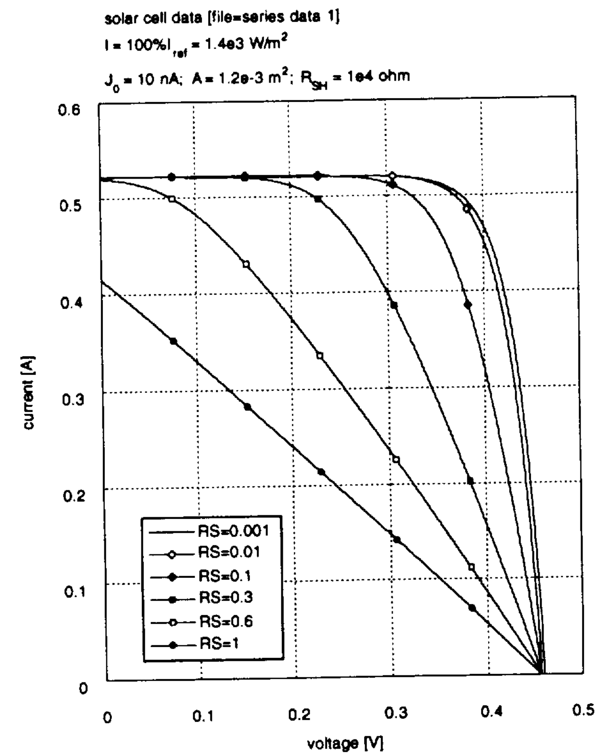

Figure 3. *Current-voltage plot of simulated solar cell degradation as function of increasing series resistance (R_S).*

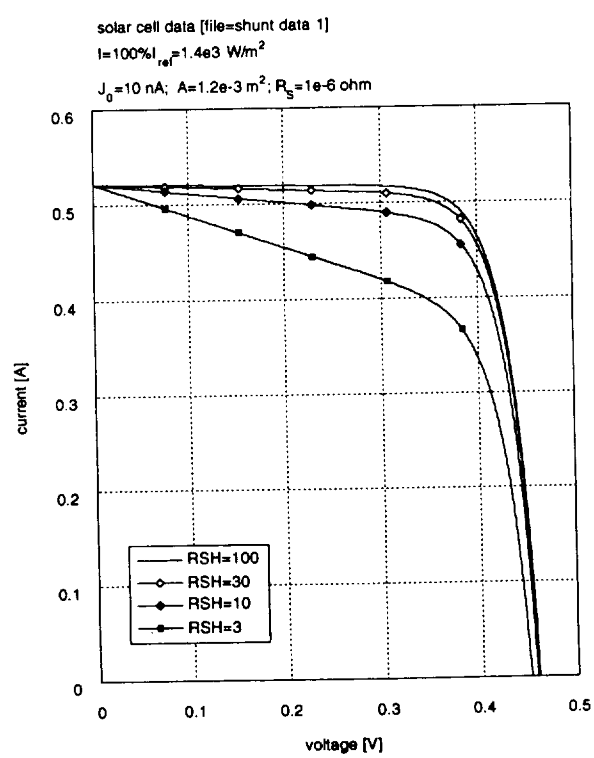

Figure 4. *Current-voltage plot of simulated solar cell degradation as function of decreasing shunt resistance (R_{SH}).*

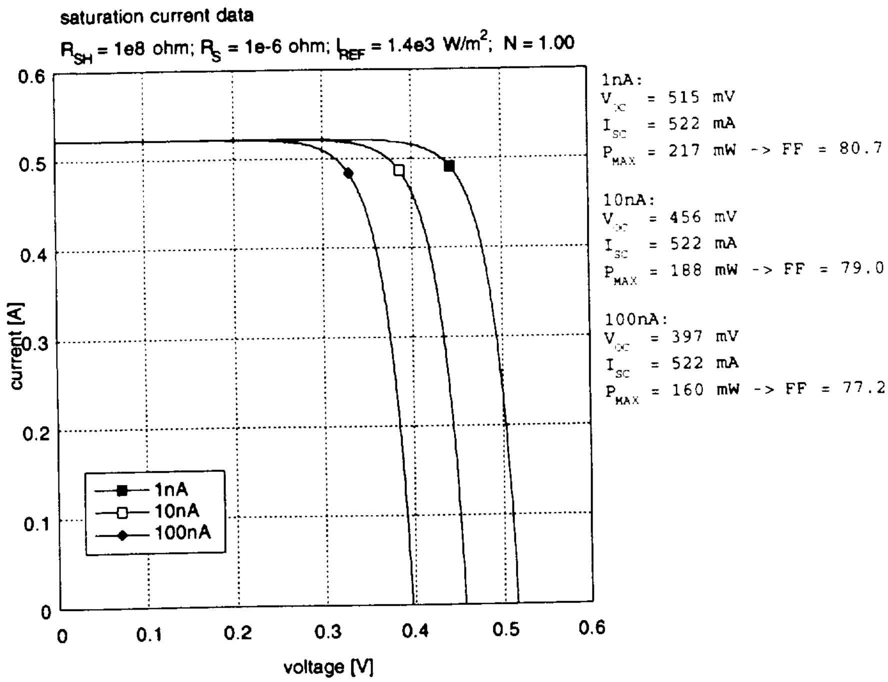

Figure 5. *Current-voltage plot of simulated solar cell degradation as a function of increasing minority carrier diffusion current (J_0).*

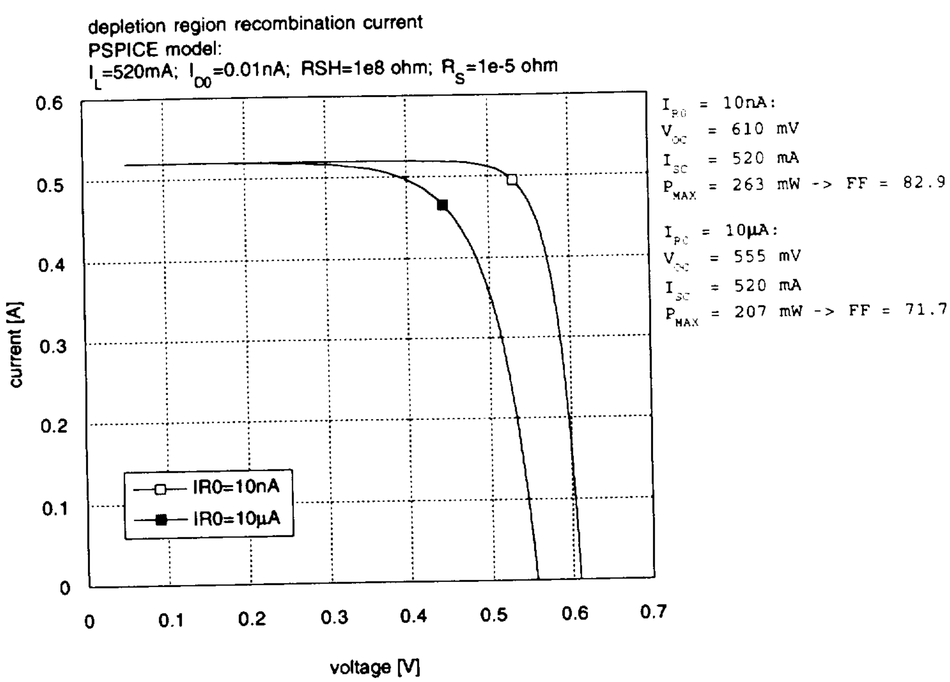

Figure 6. *Current-voltage plot of simulated solar cell degradation as a function of increasing depletion region recombination current (I_{R0}).*

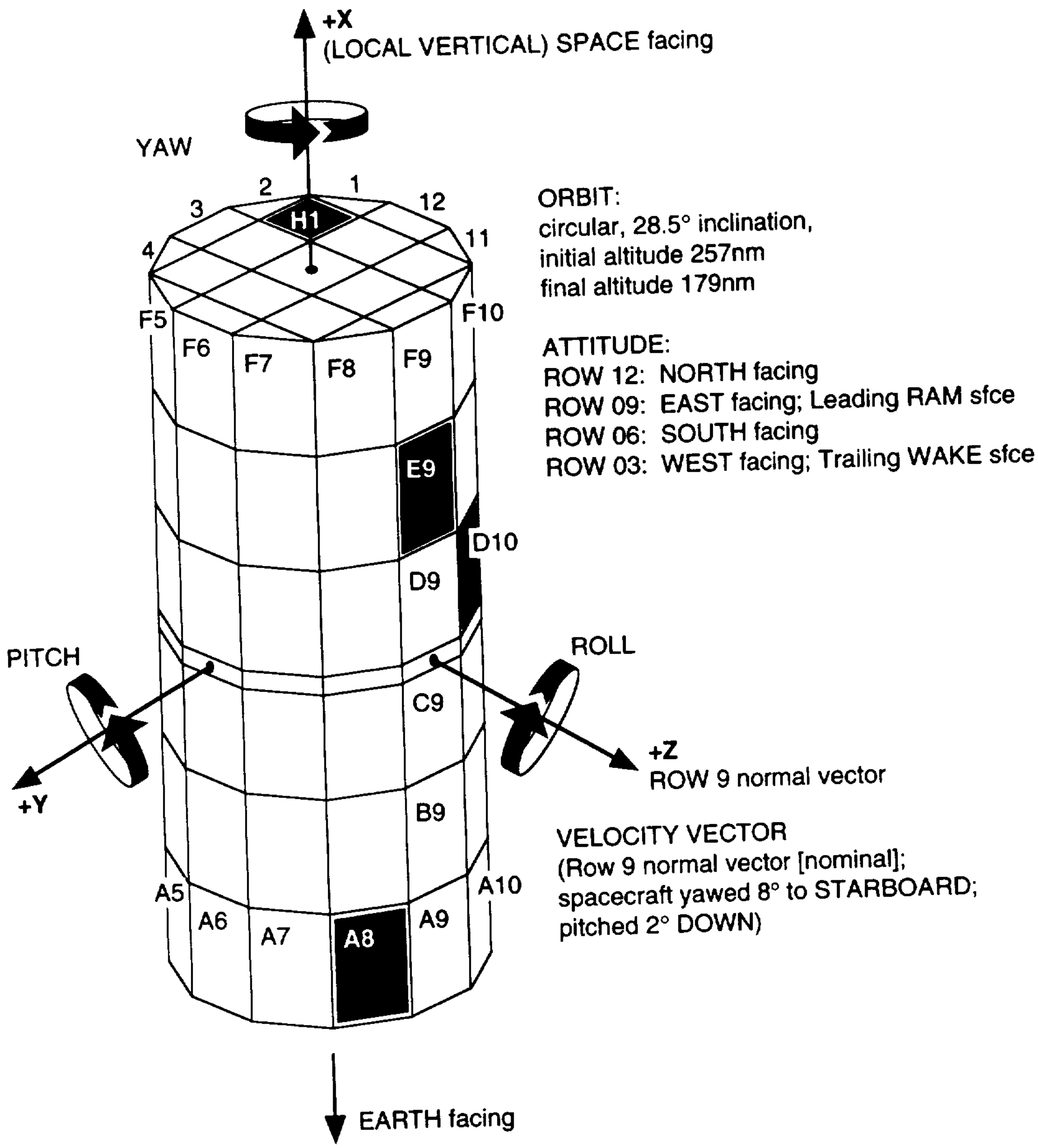

Figure 7. *LDEF orientation and location of experiments A0171 in Bay A8, A0054 in Bay D10, S0014 in Bay E9, and the power sub-system of experiment S1001 in Bay H1. Bays B4 and E3, containing experiments A0054 and S1002 respectively, are out of view on the spacecraft trailing surface.*

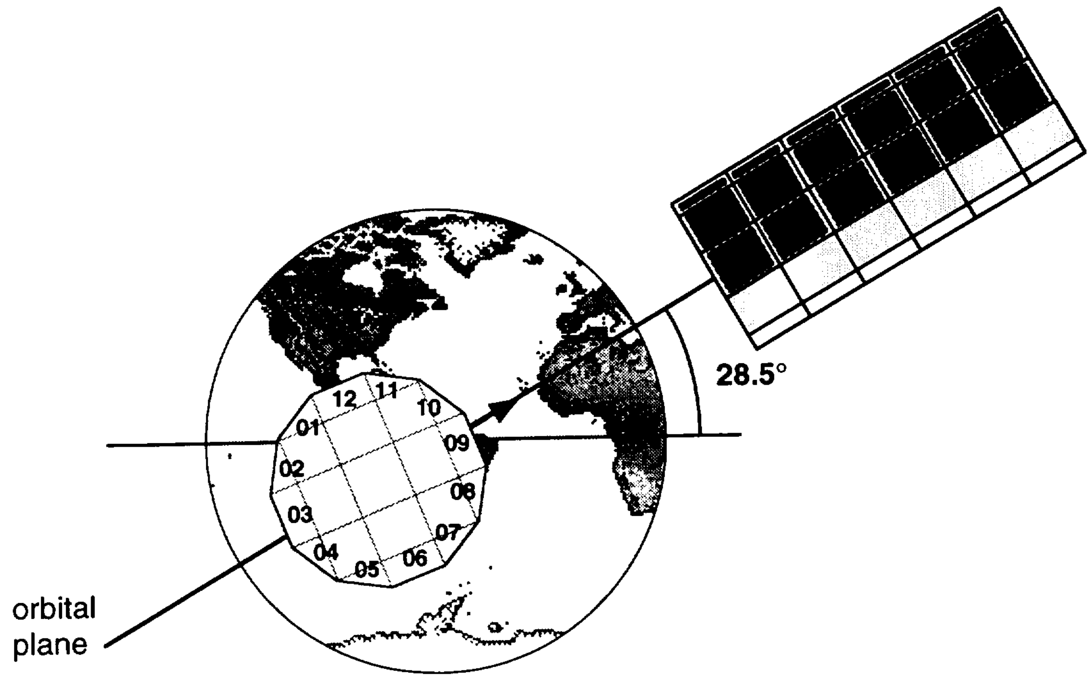

Figure 8. *LDEF flight orientation showing 28.5° orbital inclination, the relative location of the rows 01-12, and the 8.1° YAW to starboard. ROW 09 is "East-facing," ROW 03 is "West-facing," ROW 12 is "North-facing," and ROW 06 is "South-facing."*

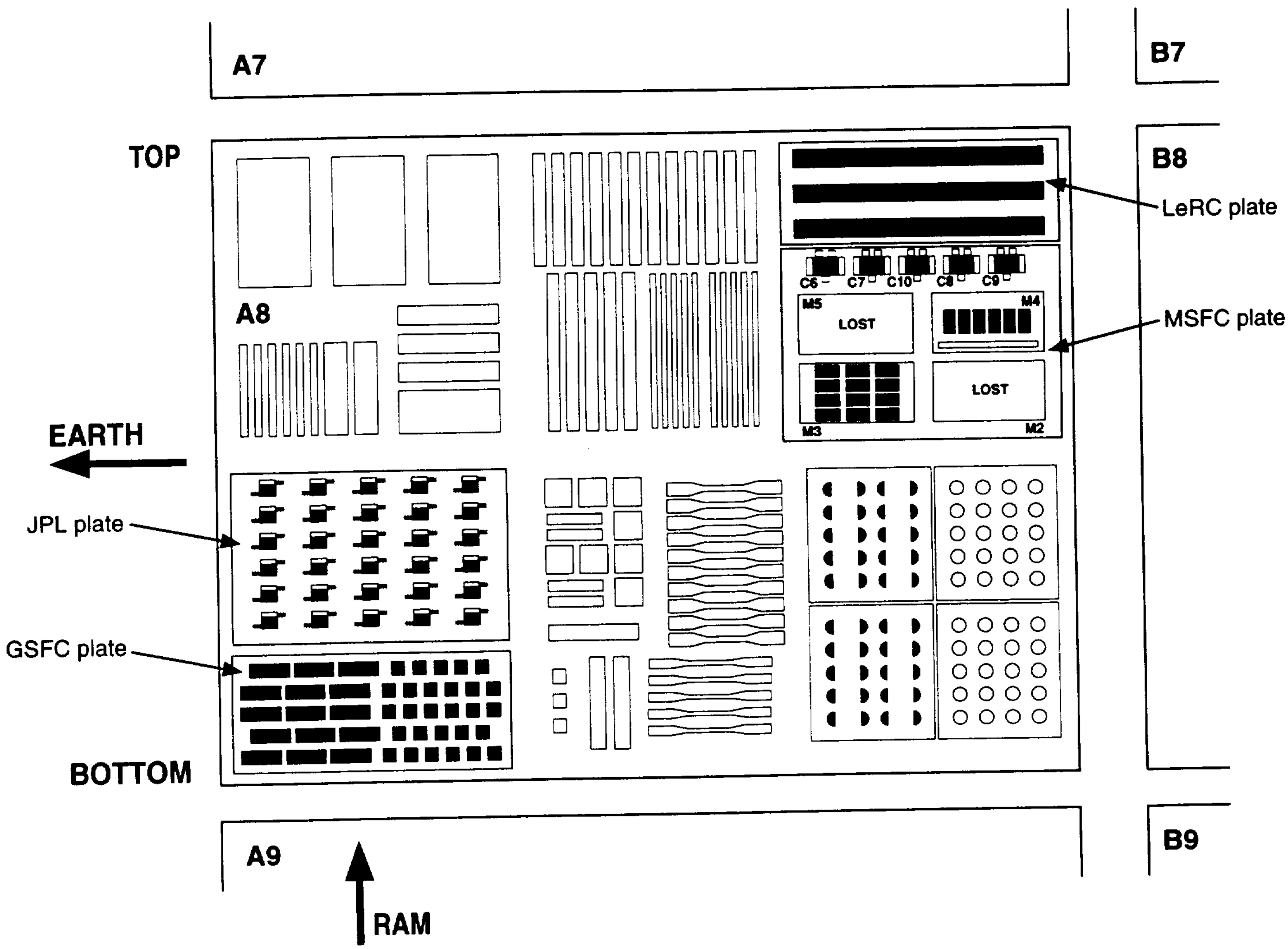

Figure 9. *Schematic of the A0171 tray (using the same protocol as the de-integration team), showing the relative locations of the JPL, LeRC, MSFC, and GSFC test plates, other experiment trays, and the vehicle orientation parameters. Note that since the experiment was mounted in a 3" deep tray the GSFC test plate was partially shielded from the AO RAM flux vector.*

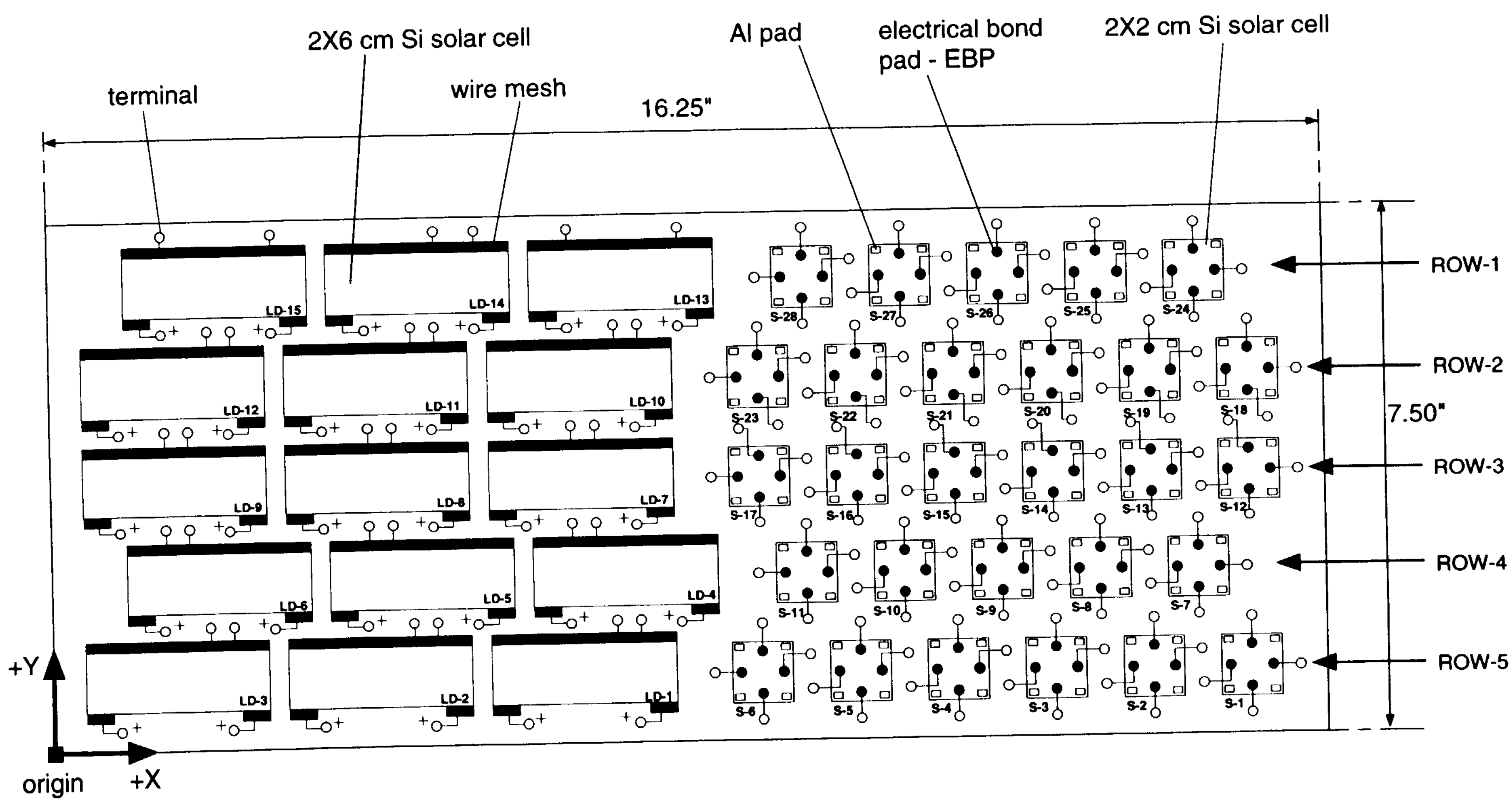

Figure 10. *GSFC test plate layout, showing electrical connections and cell identification.*

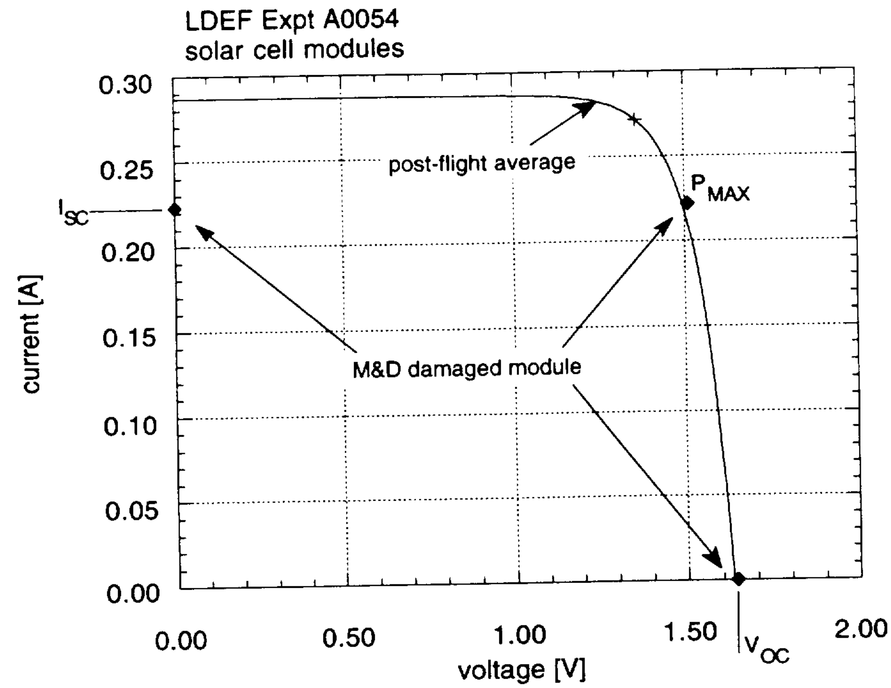

Figure 11. *Current-voltage for pre- and post-flight A0054 M&D damaged solar cell module, comparing the average post-flight solar cell module characteristics with the M&D damaged module electrical performance points. The implication of these data is that the M&D damage caused a partial shunt of the cell p-n junction with a reduction in series resistance in the bulk of the cell.*